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WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 1

PUMPING WATER FOR IRRIGATION.—WILSON

WASHINGTON
GOVERNMENT PRINTING OFFICE
1896

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UNITED STATES GEOLOGICAL SURVEY
CHARLES D. WALCOTT, DIRECTOR

PUMPING WATER FOR IRRIGATION

BY

HERBERT M. WILSON

WASHINGTON
GOVERNMENT PRINTING OFFICE
1896

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, July 9, 1896.

SIR: I have the honor to transmit herewith a paper entitled "Pumping water for irrigation," by Herbert M. Wilson, geographer, and to recommend that it be published as the first number of the series of papers "in relation to the gauging of streams and to the methods of utilizing the water resources," whose printing was authorized in the act making appropriations for sundry civil expenses of the Government for the fiscal year ending June 30, 1897, approved June 11, 1896.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

PREFACE.

This paper by Mr. Wilson is the first of a proposed series of publications relating to water supply and irrigation. The object in view in undertaking a new series is to afford an opportunity for prompt publication of short reports, generally popular in character, relating to the water resources and the methods of utilizing these, with especial reference to the employment of water in agriculture. To reply to questions arising in various parts of the country regarding the progress of the investigation of the water resources and the facts relating to the available supply of water for irrigation, power, or domestic use, it is necessary to have pamphlets which can be sent out freely, and which, in order to answer the particular needs of individuals or communities, will not be too general in character. The series of bulletins issued by the Survey would serve as such means of communication were it not for the fact that by law these must be sold, and thus can not be used for official purposes or for placing the information acquired by investigation at once in the hands of the persons seeking to know the facts. By the law authorizing this new series it is possible for the Survey to distribute these papers to correspondents and to the numerous volunteer assistants who at one time or another have kindly aided by replying to letters of inquiry or schedules asking for specific data. Without such opportunities for distribution of small publications the officers of the Survey are placed in an embarrassing position, from the fact that they are compelled to ask favors in the way of statements and data of various kinds and are yet unable in general to more than thank the persons who have freely given their time to the preparation of letters and the filling out of blanks. Even when these persons have asked for a copy of the publication embodying the information which they have furnished, it has not been possible for a bulletin to be sent unless paid for by some member of the Survey.

Arrangements have been made for following this paper with others at short intervals treating of various subjects relating to the hydrography of the country and to details such as storing, pumping, and other processes of utilizing the waters. The following topics will probably be covered during the year: Measurements of Western streams; measurements of Eastern rivers; Northeastern water power; Southeastern water power; water supply of portions of Indiana and Ohio; artesian conditions of eastern Nebraska; underground water supply of

a portion of western Kansas; recent progress in artesian developments and irrigation in the Dakotas; artesian conditions of eastern Washington and portions of Idaho and Oregon; irrigation in the Salt River Valley of Arizona; methods of irrigation in California; seepage waters from irrigation; water storage in a portion of Wyoming; well waters of Nebraska; efficiency of windmills for irrigation; sewage irrigation, etc.

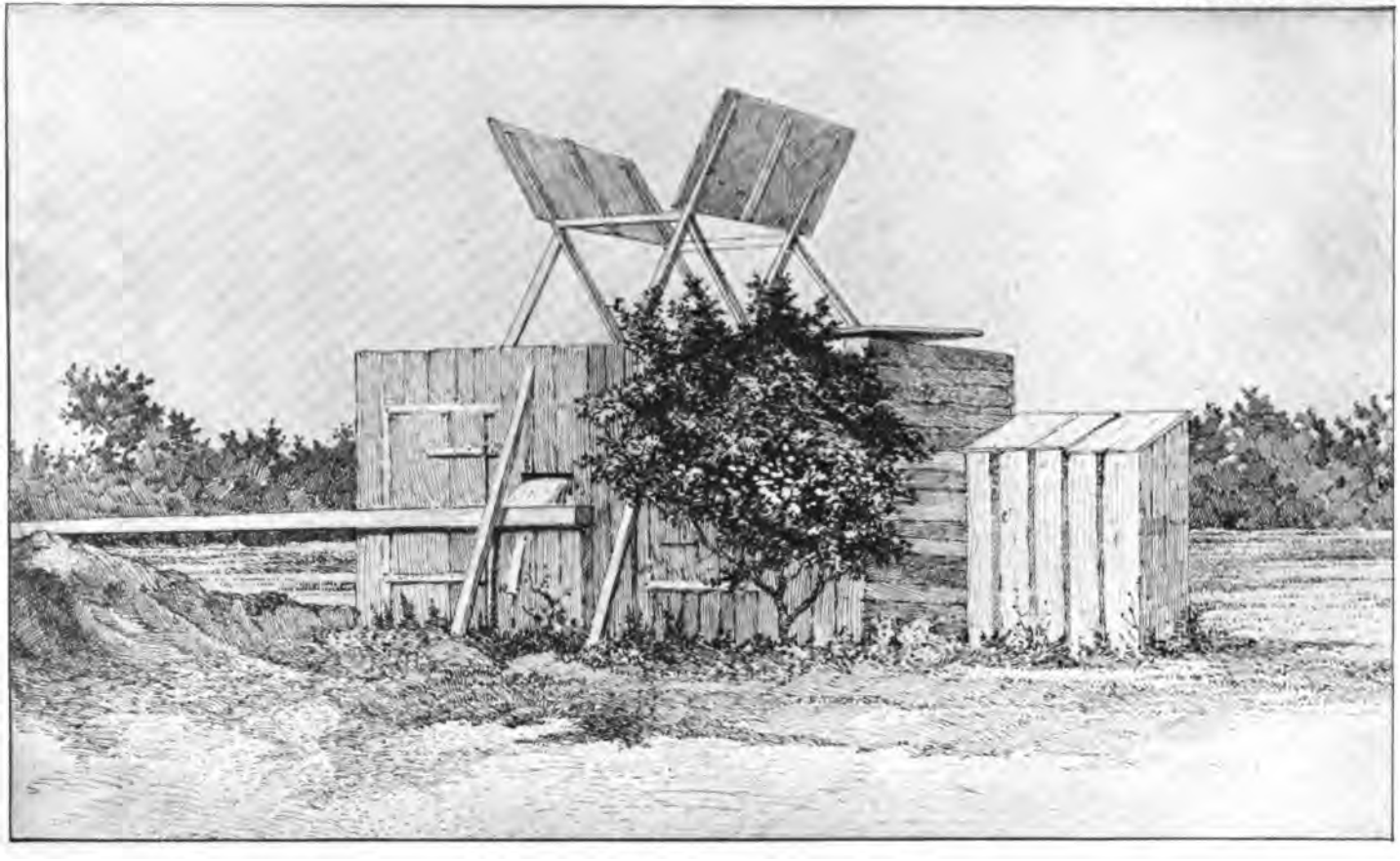
The data upon which these and other papers are based are being obtained largely through the field work of the Division of Hydrography, supplemented by correspondence carried on by means of schedules. Whenever practicable, arrangements are made with experts in various parts of the country to bring together the facts in their possession, rounding these out with additional investigation and preparing reports embodying this matter. Every effort is made, however, to preserve the distinctive character of an investigation and to push forward the work in directions where it is impossible for the individual to proceed unaided. It is not intended to bring together simply a lot of obvious facts and inferences relating to the water resources of the country, but to extend the bounds of knowledge in directions where exact information will have the greatest future value. It should be recognized that progress in new fields can never be so rapid as traveling over the old paths. It is only by bringing together clearly and concisely what is already known and building upon this that progress can be made in the utilization of the water resources of the country.

In the following paper by Mr. Wilson a general description is given of pumps and motive powers, and of windmills, water wheels, and various kinds of engines, noting the more important of these. The conditions surrounding the raising of water vary so widely that it is obviously impracticable to designate any one method as better than others, and a machine or device which to a man from one part of the country seems utterly useless may meet the requirements of some other locality. Mr. Wilson has therefore described, and in a few cases figured, devices which, while possessing no general applicability, yet contain suggestive features. It is not to be expected, for example, that in any part of the country human labor will be employed to any considerable extent in raising water, as is the case in Egypt, India, and other parts of the world; but the simplicity of the methods commend themselves, and a mention of these may serve to stimulate some inventive genius to make a practical application suitable for local needs. It is surprising to note how often the devices for raising water which in themselves are older than any written language have been reinvented and applied by the irrigators of the West. Again and again has the attention of the hydrographers of the Survey been called to the home-made devices for raising water based upon the principle of the Egyptian water wheel, or noria, or of the Persian bucket pump. These have

been devised by men who have considered the idea original with themselves, and could with difficulty be persuaded that their pet invention was old in the days of the Pharaohs.

In a new and rapidly developing country, such as the arid region, where methods of raising water for agriculture are constantly being modified and improved, it is desirable to have in mind all of the ways which have been found of value in the past. This pamphlet can by no means mention all or even a small part of these, being considered only as preliminary to more extended discussions. It is hoped that through the investigations of the Division of Hydrography a considerable body of accurate figures can be obtained concerning the methods and machinery for pumping large quantities of water now being put into operation. It may be interesting to note in this connection that as machinery is being modified to suit the requirements of lifting a large amount of water through a relatively small vertical distance, and at the least practicable expense, there is a tendency to return to the simple forms used by the primitive agriculturist, adapting these to modern machinery. For example, after trying all the complications of valves and pistons, of tight joints and complicated motions, designers of machinery are in some instances turning back to the old simple Persian wheel, which lifts water in buckets with the minimum of friction and of load to be raised.

F. H. N.



HOME-MADE WIND ENGINE, AS USED ON THE GREAT PLAINS

PUMPING WATER FOR IRRIGATION.

By Herbert M. Wilson.

INTRODUCTORY.

Until within the last decade the water supplies used in irrigation in our Western States were brought to the places of utilization almost wholly by gravity. There are, however, large volumes of water situated at such low levels that gravity will not carry it to the fields, and only in recent years have we come to a realization of the fact that this water may be raised by pumps or other lifting devices to elevations from which it will flow by gravity to the irrigable lands.

Extensive areas may be brought under cultivation through pumping after the supplies which gravity alone will bring have been entirely utilized. Not only is the water which may be raised from wells or low-lying streams available, but that which finds its way by seepage from irrigation canals and irrigated lands may be gathered into wells and pumped to the surface and again employed in irrigation. For, as irrigation is practiced, the subsoil becomes saturated, the ground-water level is raised, and much of the water delivered to the surface by gravity systems finds its way by seepage from the fields into the soil and may through pumping be used again in irrigation, thus adding to the duties of the ultimate sources of water supply.

The value of pumping for such purposes has been recognized for ages in the older European and Asiatic countries, and a large portion of the irrigation in Europe, India, Egypt, China, and Japan is carried on by such means. In Oriental countries pumping is performed almost wholly by animal or man power. In some portions of Europe, notably in Italy, some pumping is done by modern machinery, chiefly in raising water from existing low-level to high-level canals. In our own country numerous pumping plants actuated by wind, gasoline, water, and steam powers have been erected within the last few years, and they have proved so efficient and economic as to at once gain favor with Western irrigators.

The real value of pumping as a means of irrigation, and the extent to which it may be employed, are as yet scarcely appreciated. A great many windmills and some water wheels are utilized in our Western

States for this purpose, and a little pumping is done by steam and gasoline. But the value of the water supplies to be derived from lifting is sure to increase greatly as the cheapness and adaptability of this method come to be fully recognized. It is now a well-established fact that pumping occasionally furnishes irrigation water more cheaply than does gravity, both as regards first cost of the pumping plant, equivalent to the cost of water rights, and as regards the cost of maintenance and operation, which corresponds to the annual water rental or rate in the gravity system. In pumping, the source of water supply is more directly under the control of the irrigator, while he is troubled by none of the vexatious controversies arising from questions of priority of right or of water appropriation, of time of supply, and of rotation in the ditches; nor is he so likely to have his supply cut down in seasons of drought.

According to the figures given by F. H. Newell in the report on Agriculture by Irrigation, prepared for the United States census of 1890, the average first cost of water derived from gravity supplies for the whole United States was $8.15 per acre, varying between $3.62, the average for Wyoming, and $12.95, the average for California. The average annual water rental was $1.07 per acre, ranging between 44 cents in Wyoming and $1.60 in California. The average cost per second-foot of water on account of construction of some of the great gravity canals of the West, and based on the assumption that their whole supply was utilized, varied between $125 for the Bear River Canal, Utah, and $730 for the Turlock Canal, California. The cost per acre irrigated for the same works varied between $5 for the Bear River Canal and $14.50 for the Turlock Canal. The average cost per acre irrigated by some of the greater of the storage reservoirs of the West varied between $19.96 for the Hemet Valley Reservoir in California and $81.80 for the Sweetwater Reservoir in California.

On the other hand, numerous windmill pumping plants have been erected in the West, the first cost of which is equivalent to a charge of about $20 per acre irrigated, or less, while the cost of maintenance, equivalent to annual water rental, is practically nil. Hydraulic rams have been utilized in pumping for irrigation at a cost of about $10 per acre irrigated, with practically no charge for maintenance and operation. Gasoline pumping engines are extensively used in the West, the first cost of which has been equivalent to about $30 per acre irrigated, with a cost of operation of $1.25 per acre. Water-power pumping plants have been erected in the West at costs ranging from $1 to $15 per acre irrigated, and with operating charges varying between $1 and $2.50 per acre. Of steam pumping plants so far erected in the West the cost has ranged from $5 to $10 per acre irrigated, with an operating charge of from $1.50 to $3 and upward per annum per acre irrigated.

As an indication of the extent to which pumping, even in the crudest

forms, may be utilized, either to supplement gravity supplies or independently of them, it may be stated that in one small area in India, between the Ganges and Jumna canals, there are over 350,000 wells supplying water by lifting to 1,500,000 acres of crops. In Madras, India, 2,000,000 acres are irrigated by water pumped from 400,000 wells. In one small province in southern India there are over 100,000 wells, many of which have been sunk through hard rock to depths of from 80 to 90 feet and are capable of irrigating in ordinary seasons from 1 to 4 acres each. In our own country, on the great plains sloping eastward from the Rockies and on many of the broader intermontane valleys and in the great California valley, wherever the wind is comparatively constant and of relatively high velocity, vast areas of land may be brought under cultivation through irrigation by water lifted from wells by means of windmills. In like manner, streams which are flowing between steep banks may not only furnish water supplies for irrigation by means of pumping, through wind, steam, or gasoline power, but, if of sufficient size, may furnish water power for lifting. The extent to which water supplies are to be derived from such sources is yet difficult to estimate, but it is certainly within the realm of probability that eventually nearly one-half as much area may be brought under cultivation through lift as through gravity supplies.

PUMPS AND MOTIVE POWERS.

Pumps are machines for elevating water, and they may be divided into two principal parts: the pumping or water-elevating device, and the power by which this is operated. Pumps, as such, may be divided into four general classes, according to the principle on which they raise water, namely: (1) lift pumps, (2) force or plunger pumps, (3) rotary and centrifugal pumps; (4) mechanical or siphon elevators. The principle of lift and force pumping may be combined in one mechanism, and this may be either reciprocating or rotary, or it may be single or double acting.

The motive power may be derived from one of the six following sources, namely: animal, wind, water, hot air, explosive force of gas, and steam. Force, lift, and centrifugal pumps and mechanical elevators may be operated by almost any one of the various motive powers. Distinguished from these are three additional classes of pumping mechanisms, in which the motive power and the pump are inseparable. These are (1) injectors, vacuum pumps, and pulsometers, in which steam is the motive power; (2) hydraulic rams and hydraulic engines, in which water is the motive power; and (3) siphons and siphon elevators, in which atmospheric pressure is the motive power.

Lift pumps operate by drawing water through a suction pipe as the pump bucket ascends; as the bucket descends the water is forced through a valve in it, and is then lifted as it reascends. This variety of

pump is dependent for its operation on atmospheric pressure for the creation of a partial vacuum below the pump bucket.

Force pumps draw water through a suction pipe as do lift pumps, but to less heights, and the water is raised above the bucket by the action of a piston or plunger which forces it through a delivery valve. Force pumps may be single or double acting, and nearly all steam pumps are of the latter variety, the discharge of these being practically continuous, for as the water is drawn in at one end it is forced out at the other.

Centrifugal pumps depend for their action on a disk to which are attached propeller blades revolving inside a chamber. These propeller blades create a partial vacuum which lifts water, though but a few feet, into the chamber by suction, whence it is forced by the following propeller blade. Rotary pumps are practically revolving piston pumps, differing from the latter chiefly in that the propelling piece moves forward continuously.

Mechanical water elevators include not only the various patented devices by which water is raised by means of disks or buckets arranged on a revolving chain, but also the various ancient mechanisms employed in oriental lands for lifting water from wells. Among these are chain pumps, Archimedean screws, the tympanum, Persian wheel, noria, the latha or basket, the doon, the lat or paecottah of India, which is the shadoof of Egypt, the mot, and numerous other curious devices.

All the motive powers except wind may be used to operate any of the various classes of pumps. Ordinarily, however, animal power is used to operate the lighter forms of pumping machinery which are intended to elevate small quantities of water, and the common lift and force pumps and mechanical elevators of various kinds. Wind is employed almost exclusively for the operation of lift and force pumps, as it is too uncertain in its action to work well with ordinary centrifugal pumps or many forms of mechanical elevators.

The various motive powers may be divided into two general classes, according to the manner in which they are attached to the pumps. These are (1) direct-acting pumps; (2) fly-wheel and belting pumps.

Direct-acting pumps have, as a rule, no rotary motion, their action being reciprocating, both steam and water cylinders being mounted on a solid bed plate, so that the piston rod, which produces the power, has attached to it the plunger which elevates the water. Fly-wheel pumps may be direct-acting pumps or they may have the motive power at some distance from and independent of the elevating pump and be connected therewith through shafting or belting or some other mechanical device. The latter forms are usually not so satisfactory or reliable in their operation where used for irrigation, as they generally require more skilled attendance than do direct-acting pumps, though, on the other hand, their efficiency is often higher.

In the choice of pumping machines the irrigator should consider, among other things, the motive power which is most available and cheapest for his purposes, and the quantity and accessiblity of his water

supply. Having gotten from these considerations an idea of the general form of pumping machine which will best suit his purposes, he will do well either to consult a mechanical or an irrigation engineer or, if the extent of his enterprise will not warrant this, to obtain advice from various makers of the form of pumping machine which he anticipates using. These persons will furnish him with details of cost and assist him to select the variety of machine best suited to his purpose, and he will thus be able to choose the most economic and efficient apparatus.

The pump and motive power which are to be employed in each particular case depend on the service to be performed and on various local modifying conditions. The variety of pump must be chosen according as greater or less volumes are to be elevated to greater or less heights. The motive power must be selected according to the pump chosen, the work to be done, and the fuel available, be this animal, air, water, gasoline, wood, or coal. Where means are limited and the area to be irrigated is small, the motive power chosen will usually be either animal or water. The first is cheapest of installation, but least economical, and the latter is next cheapest, providing a sufficient water supply is available for the operation of an ordinary mid-current undershot wheel, a noria, or a hydraulic ram. Where the area is small but the means at the disposal of the irrigator are less limited, animal power will usually be left out of consideration, and the choice will rest between wind, water, hot air, gasoline, and steam pumping engines. If the wind be reasonably steady and the facilities for the construction of a storage tank be good, wind motors, though not less expensive to install than some others, and not the most reliable, are least expensive and troublesome to maintain and operate. Where water is abundant, it furnishes, through water wheels, turbines, or water engines, the next least expensive power to maintain and operate, though not the cheapest to install. The class of water motor selected will depend wholly upon the fall and volume of motive power available and the height to which the water is to be raised. Hot-air and gasoline engines furnish the most reliable power for pumping water, and are less difficult to operate than steam engines. Gasoline engines are especially economical where coal or wood are expensive, though hot-air engines have a wide adaptability in the variety of fuel which they may utilize. Steam engines, where coal is cheap, furnish the most satisfactory motive power, but are generally not so economical to operate, especially where small areas are to be irrigated. For the pumping of large volumes, water and steam are the only competing motive powers.

The irrigator who proposes installing a pumping plant should consider all the various circumstances which affect the case under consideration. He should carefully weigh the necessity of having a permanent and steady supply, the inaccessibility of the plant for repairs or replacement of broken parts, the relative cost and accessibility of different kinds of fuel or of water, and the degree of intelligence and skill possessed by those who are to operate the machine employed.

ANIMAL MOTIVE POWERS.

Among the oldest and best known of these is the common domestic well sweep, which is the paecottah of India (fig. 1) and the shadoof of Egypt. In India this is operated by from one to two men who labor from six to eight hours daily and by its use raise from 1,000 to 3,000

FIG. 1.—Raising water from well in India by paecottah.

cubic feet per day. This apparatus is usually employed for but small lifts of from 5 to 12 feet, though under the name of shadoof in Egypt it is commonly employed for much greater lifts by using a series of several sweeps arranged one above the other, as illustrated in fig. 2. By

the latter means three men will irrigate from 2 to 4 acres a season. The average cost of irrigation by this means has been estimated in central India to be about $5 per acre irrigated. The paecottah consists essentially of a leathern or earthen bucket hung from the light end of a pole which is pivoted near its farther extremity and oscillates in a vertical plane, the short end of the pole being counterbalanced by a weight, so that the bucket when full requires but little force to raise it. The man working this contrivance stands on the edge of the well and uses his weight to depress the bucket into the water, whence it is raised largely by the force of the counterweight and the water is delivered into a small ditch which leads it to the irrigable fields.

Others of the mechanical devices employed in India for utilizing man power to lift water are the latha, or basket (fig. 3), and the doon (fig. 4).

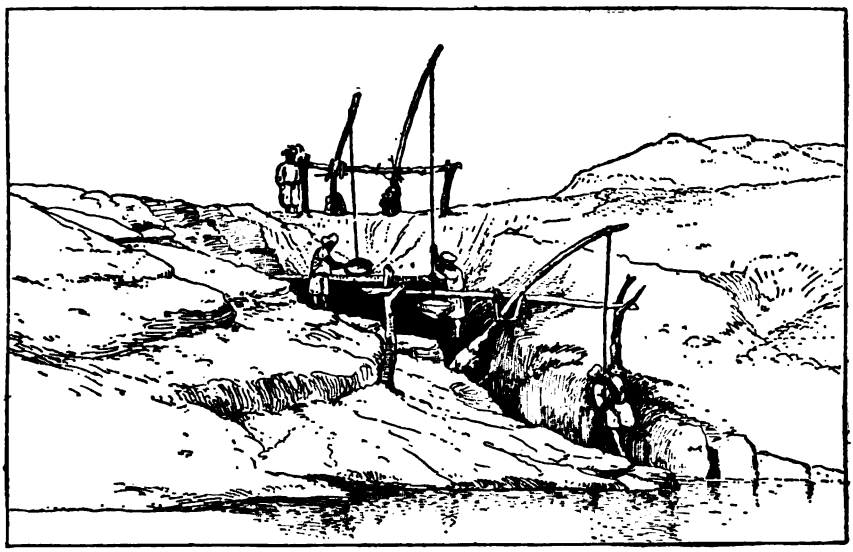


FIG. 2.—Series of shadoofs as used in Egypt.

The former is used for very small lifts of from 2 to 4 feet, and is operated by swinging the basket backward and forward in such manner that in swinging in one direction it dips into the water and is filled, and on its return to the farther end of its oscillation it is skillfully twisted so as to throw the water into a ditch. This apparatus is always operated by two men and is estimated to be capable of lifting 20,000 cubic feet of water 1 foot in height in ten hours, and the cost of its operation in India is estimated to average $3 per acre irrigated, though this figure is doubtless too low. The doon is likewise used for very small lifts, and consists of an oscillating trough[1] pivoted near its center, so that one end is alternately pressed into the water and raised above the level of delivery, the water flowing from the other end into the ditch. The

[1] Irrigation Works in India and Egypt, by Robert Burton Buckley, 1893, 348 pp.

weight of the water is partly balanced by a counterpoise, so that the man who stands over the water on the plank can depress the end of the doon into the stream by his foot, and then by stepping upon the

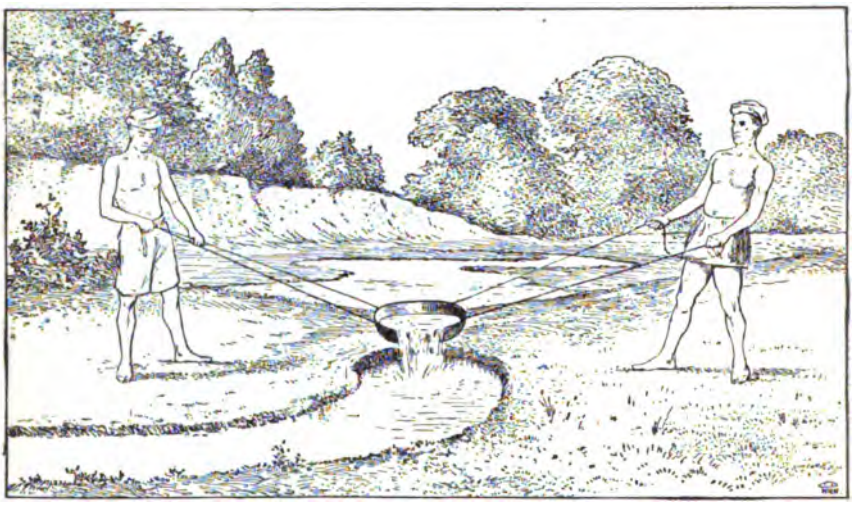


FIG. 3.—Swinging water by basket, or latha.

plank he can, with a slight exertion, slope the trough to the point of delivery. This apparatus is quite efficient for trifling lifts, and is estimated to irrigate 1 acre at an average cost of $1.60, Indian wages.

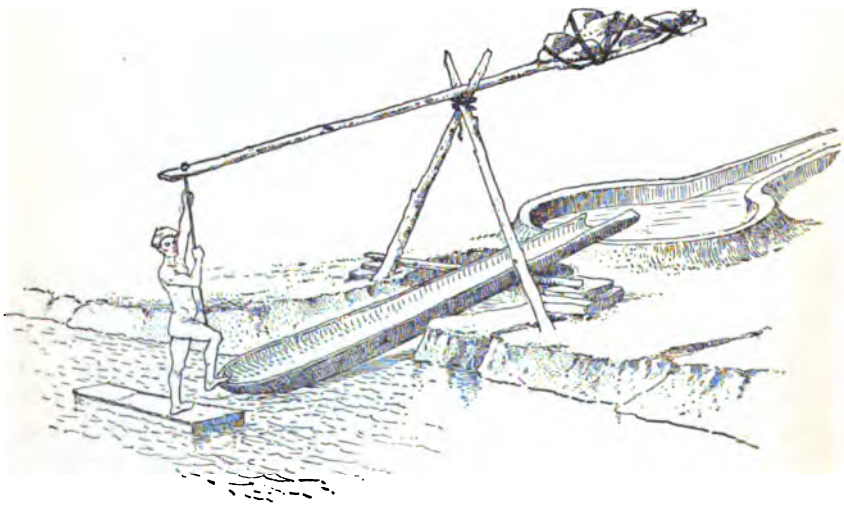


FIG. 4.—Using the doon, or tilting trough.

Of the mechanical devices used for lifting water by means of animal power, the more prominent are the mot and the Persian wheel. The mot (fig. 5) consists of a rope passing over a pulley and extending down into the well, and to the end of this is attached a bucket or other recep-

tacle. This is raised by two bullocks walking away with the rope down an incline, and thus drawing the bucket to the top of the well, where it is emptied into a distributing ditch. These animals are frequently so well trained that after reaching the bottom of their walk they return backward and at quite a rapid rate up the slope, while at other times they are trained to turn around and walk forward up the slope, again turning as they reach the top. The mot is frequently employed in lifting water from depths as great as 40 to 50 feet. It is operated by one or two men, according to the mode of construction of the water bag. In some cases this has to be emptied by one man standing at the well curb while another drives the bullock; in other cases the bag is emptied automatically by an ingenious attachment of the rope to an opening at its lower end, and one man only is employed, to drive the animals. With the mot it is estimated that two bullocks work-

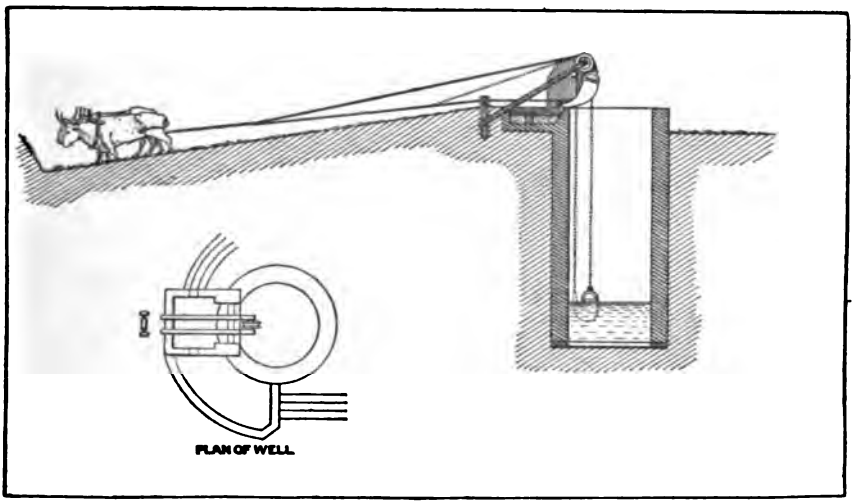


FIG. 5.—Bullocks lifting water by bag, or mot.

ing ten hours a day will irrigate 3¾ acres in a season of ninety days, and the average cost of irrigation by this means is $3.50 per acre irrigated.

Perhaps the oldest, and certainly the most extensively used, of animal motive powers is the Persian wheel, which is employed commonly throughout India, Asia Minor, and Egypt. This consists of a vertical wheel (fig. 6) to the outer rim of which are attached buckets which dip into the well, or over its rim is hung a rope to which are attached the buckets, and these hang below the lower periphery of the wheel and dip into the well below. As the buckets reach the upper circumference of the wheel they spill their contents into a trough which leads the water through ditches to the irrigable fields. With the Persian wheel two bullocks will lift 2,000 cubic feet of water per day. This device is not uncommonly employed for lifts as high as 25 to 100 feet.

Recently there have been patented in this country a number of adaptations of the Persian wheel, skillfully designed and constructed in such manner as to be more efficient than the ancient oriental device. One of these consists of large metal buckets hung on heavy linked chains which revolve over the vertical wheel and dip into the source of water supply beneath. This wheel is operated by iron-cogged gearing, turned by sweeps to which one or more draft animals are attached (fig. 7). These wheels have capacities varying from 500 cubic feet per hour for one horse to 2,000 cubic feet per hour for four horses for a depth of 20 feet, and their first cost ranges between $200 and $500. There are also on the market in this country a number of mechanical devices for utilizing animal power in pumping, consisting of various forms of sweeps to be operated by horses walking in a circle or by treadmills for utilizing horse, bullock, or sheep power through gearing and shafting. Most of

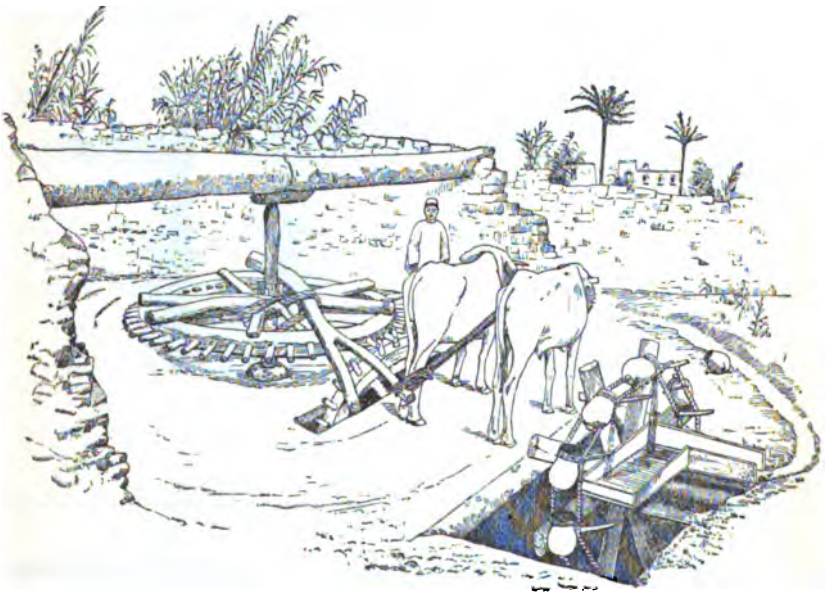


FIG. 6.—Persian wheel driven by bullocks.

these are simple in construction and operation and are not liable to get out of order. They furnish motive power usually for lifting water by means of mechanical elevators or force or centrifugal pumps, and are, with their pumps, capable of lifting sufficient water with a two-horse device to irrigate from 2 to 5 acres per season, while this amount could be at least doubled if a storage tank of sufficient capacity were provided for retaining water during periods when not wanted for immediate use.

An ingenious device for lifting water by man power is the double zigzag balance of Asia Minor and Egypt. This contrivance (fig. 8) consists of a double series of wooden troughs or gutters, the extremities of which are fastened and rise one above the other at an acute

angle. At the junction of each pair of troughs are placed wooden valves to prevent the return of water. This balance is suspended at its upper end on a level with the irrigating ditch, and is caused to oscillate about this as a center, much as does a pendulum, the motion being produced by a couple of men pulling on ropes. The lower ends of the troughs dip into the stream from which the water is to be lifted, and at every oscillation each series of troughs empties its water into that immediately above, until it is finally lifted to the summit of the balance, whence it is discharged into the irrigating ditch.

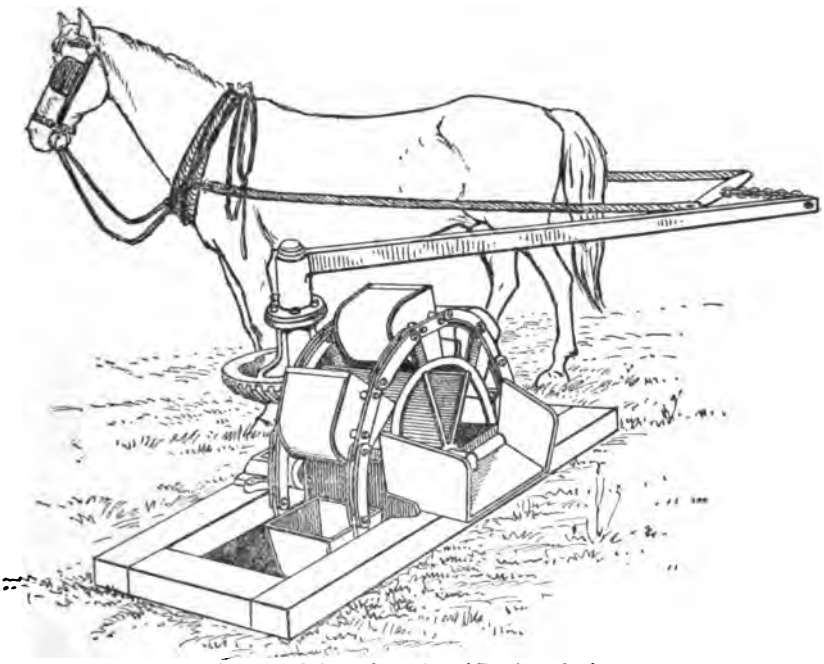


FIG. 7.—Modern adaptation of Persian wheel.

WINDMILLS.

Irrigating water is now being extensively pumped by windmills in various portions of the West, notably in the San Joaquin Valley of California, in Kansas, Nebraska, and the Dakotas, and elsewhere on the Great Plains east of the Rocky Mountains. Until recently windmills have been most extensively employed for pumping water for domestic use, but as water supplies for irrigation have become scarcer, and as practical farmers have come to appreciate the value of irrigation, they have in seeking new water supplies resorted quite extensively to windmills as motive powers for pumping water. The chief objection to windmills for this purpose is that they are dependent upon the force and regularity of wind for their operation, and as a result they do not urnish as steady and reliable a power as do water, steam, and other agents. This objection is, however, not serious on the Great Plains between the Rocky Mountains and the Mississippi River, especially if

storage reservoirs are employed as an adjunct to the mills, for in that region there is, throughout most seasons, a sufficiently steady and powerful wind to keep the wind wheels constantly turning. In other portions of the West the winds are less certain in their action, and may fail the farmer at the very time when he is most in need of a water supply.

Windmills are too frequently employed to pump water for irrigation

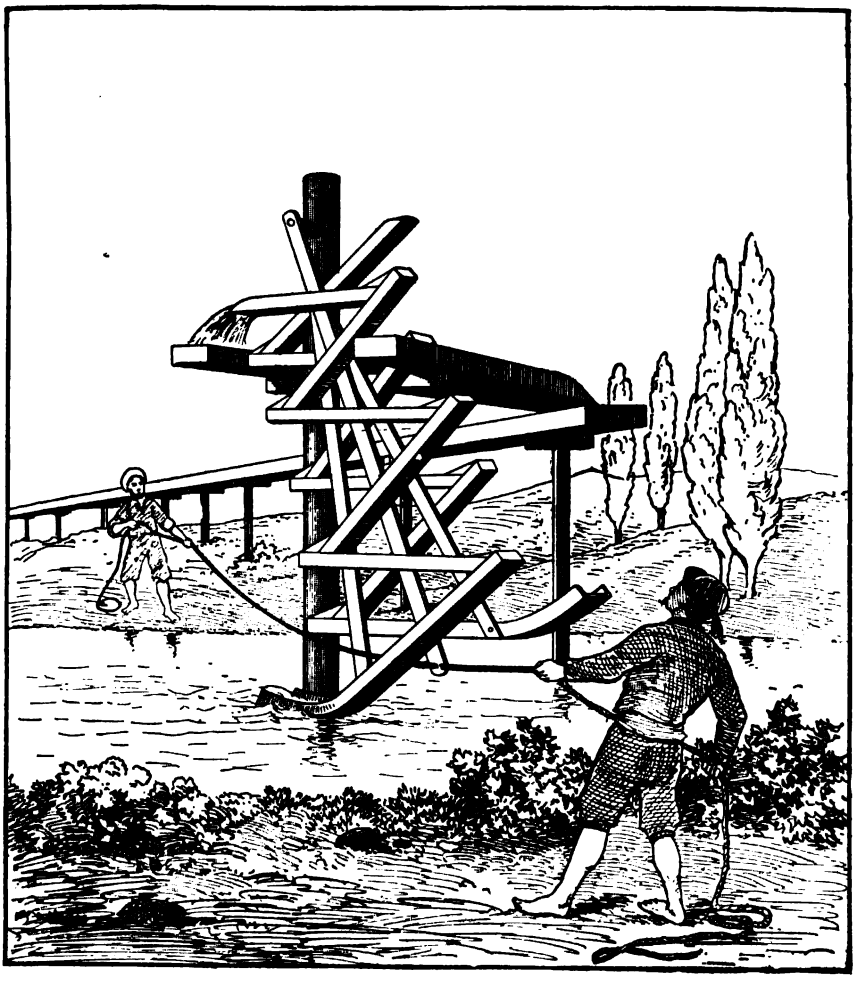


FIG. 8.—Double zigzag balance.

either from the uncertain supplies derived from drive wells or without the aid of a storage tank or reservoir in which to retain the surplus pumped at such times as it is not utilized in irrigation. As a result the supplies which they furnish are insufficient and unsteady, and this has led to their condemnation. The fault in such cases has not been with

the mill but with the user. In order to obtain good results from windmills they should not be used where the wind is uncertain and shifting, or in connection with a poor pump, or where a water supply equal to their full pumping capacity is not available; and they should invariably be supplemented by an ample storage reservoir.

The wind may blow at any time during the twenty-four hours, and is no more likely to blow in the daytime than at night, when water is not used in irrigating the fields. It is also likely to be as active at seasons when irrigation is not in progress and during the late winter and spring months as when water is being run upon the fields. For security, therefore, and in order to irrigate a reasonable area from a pump of given capacity, ample storage room should be provided for the water which can be pumped during several weeks. This storage room may be obtained by using one of the various forms of elevated wooden tanks supplied by windmill makers; or, better, if the windmill can be located at a high point on the farm an artificial reservoir may be constructed of earth at this point and be suitably lined with earth puddle or asphaltum. It should, if possible, be sheltered from the sun by a roof, so as to decrease losses by evaporation. Such a storage reservoir can easily be given sufficient capacity to retain a much larger volume of water than can economically be stored in a wooden tank.

The amount of work which a windmill will perform depends on the force and steadiness of the wind, the size of the wind wheel, its design and construction, and its location. An average wind velocity of not less than 6 miles per hour is required to drive a windmill, and, on an average, winds exceeding this velocity are to be had during eight hours per day; hence, about two-thirds of the total wind movement is available for work. According to reports of the United States Weather Bureau, the average wind movement of the entire country is about 6,000 miles per month, or over 8 miles per hour. These averages are somewhat exceeded in Dakota, where the hourly velocity is from 10 to 12 miles, as it is in Nebraska, Kansas, and neighboring States, while they are too great for some other portions of the arid West. The following table gives roughly the force of the wind for ordinary velocities:

TABLE I.—*Wind velocity and power.*

Miles per hour.	Velocity in feet per second.	Pressure per square foot, in pounds.	Miles per hour.	Velocity in feet per second.	Pressure per square foot, in pounds.
6	8.8	.1	30	44.0	4.4
10	14.7	.5	35	51.3	6.0
15	22.0	1.1	40	58.7	7.9
20	29.3	2.0	45	66.0	10.0
25	36.7	3.1	50	73.3	12.3

Table II, which is derived from Mr. A. R. Wolff's treatise on the windmill,[1] and is based on scattered data of actual performances, shows the capacity of a windmill having various diameters of wheels with an assumed average velocity of wind of 16 miles per hour and working eight hours per day.

TABLE II.—*Capacity of windmill.*

Size of wheel, in feet.	Revolutions of wheel.	Gallons of water raised per minute to an elevation of—						Horse-power developed.
		25 feet.	50 feet.	75 feet.	100 feet.	150 feet.	200 feet.	
10	60 to 65	19.2	9.6	6.6	4.7	.....	.....	0.12
12	55 to 60	33.9	17.9	11.8	8.5	5.7	.....	.21
14	50 to 55	45.1	22.6	15.3	11.2	7.8	5.0	.28
16	45 to 50	64.6	31.6	19.5	16.1	9.8	8.0	.41
18	40 to 45	97.7	52.2	32.5	24.4	17.5	12.2	.61
20	35 to 40	121.9	63.7	40.8	31.2	19.3	15.9	.78
25	30 to 35	212.4	107.0	71.6	49.7	37.3	26.7	1.34

According to Mr. Wolff's estimate, the cost of operating a windmill for a 25-foot lift, including interest on first cost and charges for maintenance, ranges from ¾ cent per hour for a 10-foot wheel to 2½ cents for a 16-foot wheel and 4¼ cents for a 25-foot wheel. From an inspection of the foregoing, it is evident that the windmill is one of the most economical of motive powers. Its operation calls for no expense for fuel and little for attendance or repairs. In comparison with it the steam engine requires large expenditures for fuel, repairs, and attendance, and nearly all water motors call for heavy outlay in providing and maintaining their water supply as well as for repairs and attendance. It appears that on the average the economy of a windmill is at least one and one-half times that of a steam pump, while it has an additional economy over the latter because of the attendance and repairs demanded by the steam boiler.

Extensive experiments with a view to obtaining a comparison of the efficiency of various windmills have been recently made by Mr. J. A. Griffiths in Australia. The highest net efficiency observed in Mr. Griffiths's experiments with the wind blowing 7 miles per hour was 25 per cent. Table III gives the results of his experiments for the five American-made wind wheels tested.[2]

[1] The Windmill as a Prime Mover, by Alfred R. Wolff, M. E., John Wiley & Sons, New York, 1890, 161 pp.

[2] Windmills for raising water, John Alfred Griffiths: Minutes of Proceedings of the Institution of Civil Engineers, Vol. CXIX, London, 1895, pp. 321-343.

TABLE III.—*Capacities and efficiencies of several windmills.*

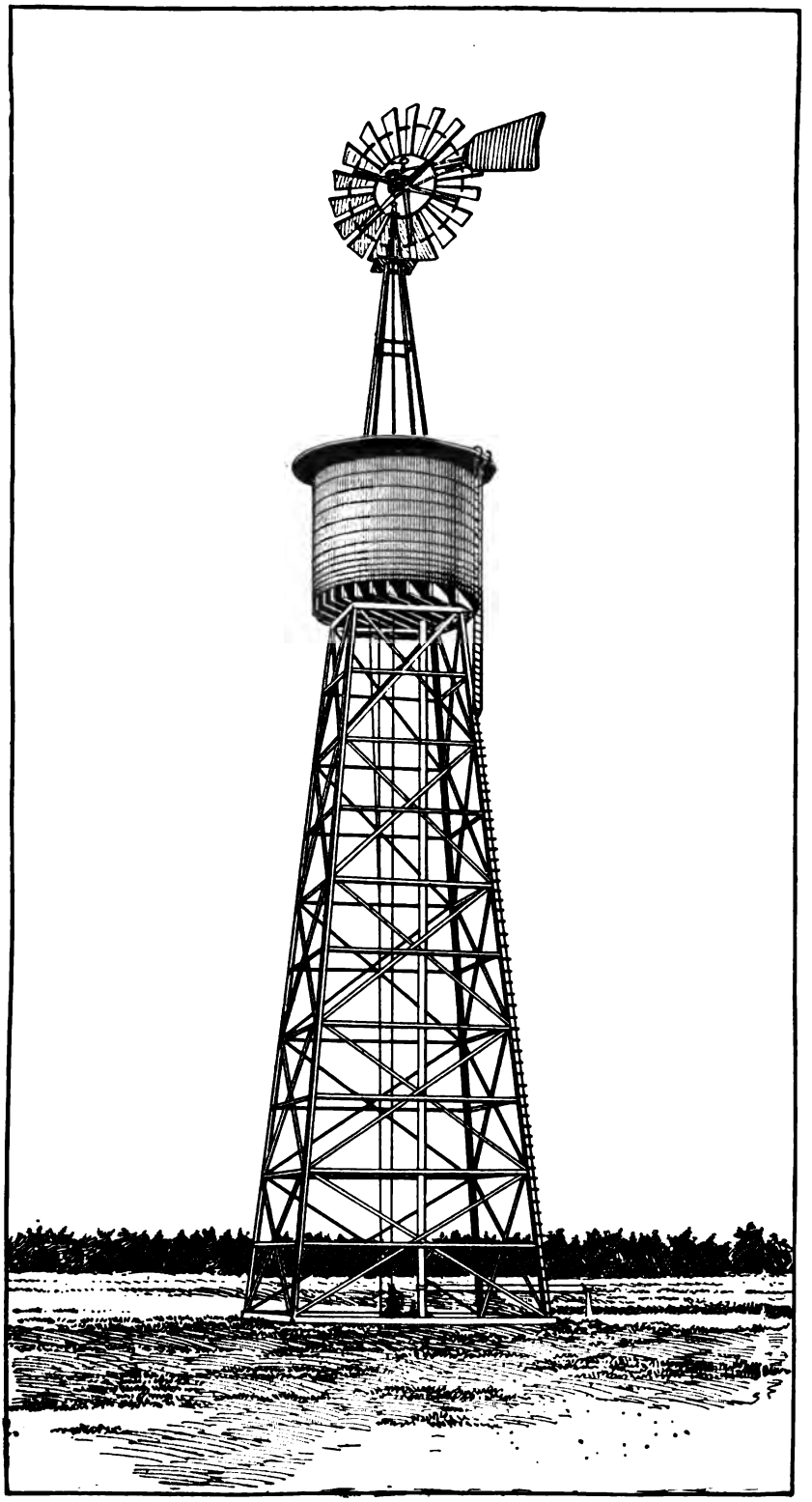
	Stover solid hand-control rudder.		Perkins solid automatic rudder.	Althouse folding rudderless.		Carlyle automatic rudder.
Outer diameter of sail wheel ..... feet..	11.5	11.5	16.0	14.2	10.2	9.8
Inner diameter of sail wheel ..... do...	4.5	4.5	6.0	4.5	3.8	4.2
Gross area of sail wheel ..... square feet..	104	104	201	157	81	80
Weather angle at outer ends of vanes ..... degrees..	43	43	36	30	28	50
Diameter and stroke of pump ..... inches..	3 by 4	3 by 4	3 by 10¼	3 by 10	3 by 4⅝	3 by 4
Average head of water during tests ..... feet..	29.2	61.2	39.0	66.3	38.7	30.7
At maximum efficiency:						
Velocity of wind per hour ..... miles..	5.8	6.5	6.0	7.0	8.5	6.0
Velocity of mill per minute ..... revolutions..	13	13.3	7.5	12.6	20.5	12.5
Actual horsepower	.011	.025	.024	.065	.028	.012
Horsepower per 100 square feet of gross area	.011	.024	.012	.041	.035	.015
Maximum net efficiency ..... per cent..	8.7	14.4	8.9	19.3	9.0	10.4
In 100 average hours, calm locality:						
Average quantity of water lifted per hour ..... gallons..	153	135	259	267	115	145
Average continuous horsepower developed per 100 square feet.	.022	.040	.025	.057	.028	.028
Average continuous gross horsepower developed	.023	.042	.050	.089	.023	.022
Average net efficiency ..... per cent..	2.1	3.9	2.5	5.5	2.7	2.7
In 100 average hours, windy locality:						
Average quantity of water lifted per hour ..... gallons..	287	271	525	540	237	270
Average continuous horsepower developed per 100 square feet.	.041	.080	.051	.115	.057	.052
Average continuous gross horsepower developed	.043	.083	.102	.18	.046	.042
Average net efficiency ..... per cent..	.28	1.11	.71	1.59	.78	.72

While designed on lines somewhat similar to those of a water wheel, a wind wheel differs from the latter in that it is wholly immersed in a sea of air, while the water wheel is acted upon by a limited current of water; therefore, while the common paddle wheels of an undershot water wheel develop considerable power, as one side only is immersed in the stream, no result can be obtained by using such a form of wind wheel unless one side of the wheel be screened from the air. This effect is obtained in a crude wheel used in some portions of the West, and known variously as the Wind Rustler, Jumbo, or Mogul windmill (illustrated on Pl. I). Such a contrivance is of course less efficient and less reliable than the regular form of windmill, because it is placed so near the ground that it does not receive the full force of the wind. Moreover, the directing of the mill to the wind is not under the control of the irrigator, and it will accordingly operate only when the wind is blowing in a direction nearly at right angles to its horizontal axis. Such a contrivance may serve as a makeshift for the pioneer who does not possess means with which to purchase a well-designed wind wheel, enabling him to bring under cultivation a trifling area of land, and to get a start in life. A number of Moguls are successfully employed in the West which have wheels of 14 to 18 feet diameter, 6 to 8 fans of about 2 or 3 by 10 to 15 feet, and are each capable of pumping sufficient water to irrigate 1 to 2 acres with a 25-foot lift. Such a contrivance costs from $20 to $100, or even more, according to the amount of hired labor employed in its construction.

The well-known forms of windmills consist of arms, cross bars, and clothing, and their vanes are made plane, warped, or concave. The older type of cloth or canvas-sail mill is common in Europe, especially in Holland, and has generally four arms. The narrow part of the sail is usually covered with a wind board, and the broader with wind slats of wood or with sailcloth. Modern American mills differ from the older European type in that they are chiefly of the propeller form, and instead of a small number of sails of considerable width are made with a great number of blades or slats of small width. They also differ in appearance from the European mill, as the wheel presents a closed surface as compared with the large open spaces between the arms of the European sail wheel. As a result of this mode of construction, the American mill is lighter in weight as well as in appearance than the European mill, and though the wide angle of the vane is not so advantageous as in the sail mill, the surface presented for a given diameter is sufficiently greater to more than compensate.

The direction of the wind is changeable, and, in order that the shaft on which the wheel revolves may be properly directed toward it, its support must be movable, so that it can revolve about a vertical axis. This revolution is effected in various manners in the old European[1] mills, and, according to the method employed, they may be divided

[1] The Mechanics of Engineering and of Machinery, Weisbach and Du Bois, Vol. II, Hydraulics and Hydraulic Motors, John Wiley & Sons, 1889.



into three classes: the post mill of Germany, the tower mill of Holland, and a type midway between these two (fig. 9), being like a tower mill in which nearly the whole mill revolves, as in a post mill, not merely the upper portion alone, as in the tower mill proper. In the post mill the entire building, wheel and all, revolves about a central fixed column or post. In the tower mill the dome-shaped cap, which is

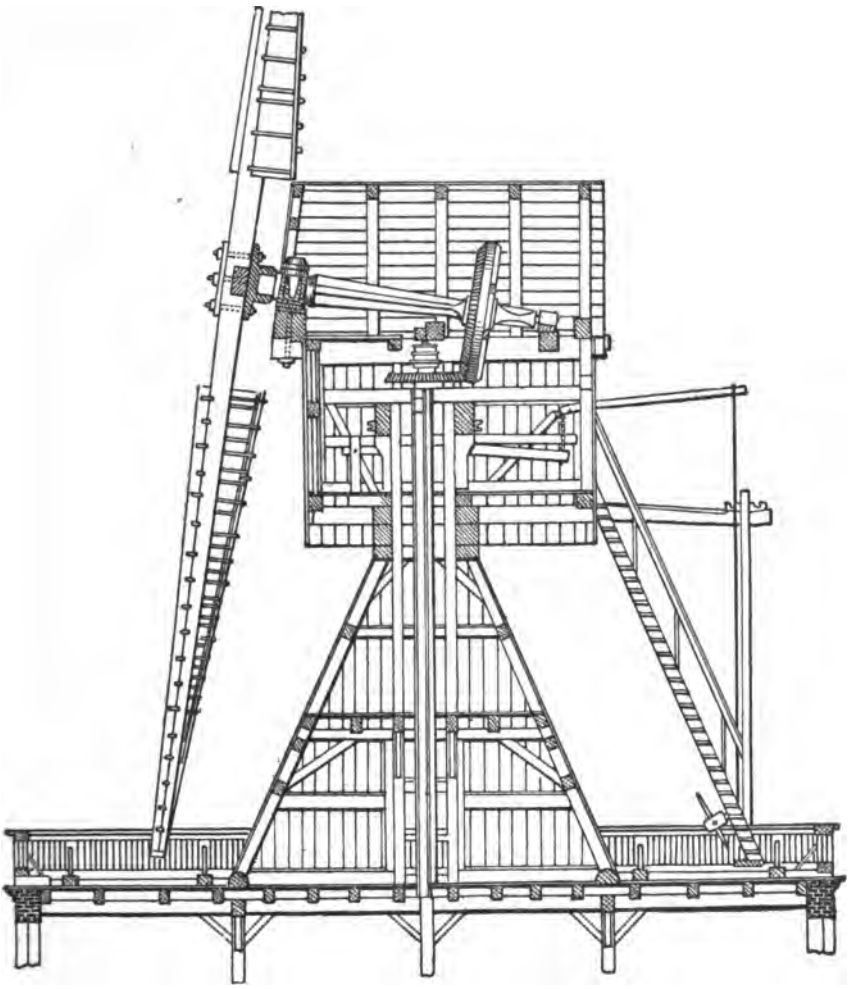


FIG. 9.—Old type of windmill, mounted on central column.

the only movable portion of the mill, rests on a stationary tower of wood or masonry. The wind shaft carrying the wheel is set at a slight inclination to the vertical. This shaft transfers its power by means of cogwheels to the vertical shaft which turns the mill and actuates the pump. The wheel is turned in the direction of the wind by means

of a lever or hand wheel or by means of a large vane or wind wheel (fig. 10) attached to a secondary axis.

The several types of American windmills are distinguished by the form of the wheel and the mode of regulating or governing its position and direction so as to obtain a uniform power and rate of revolution under varying wind velocities. These mills may be divided into two principal classes, namely: (1) sectional wheels with centrifugal governor and independent rudder, and (2) solid wheels with side-vane governor and independent rudder. In addition to these are a number

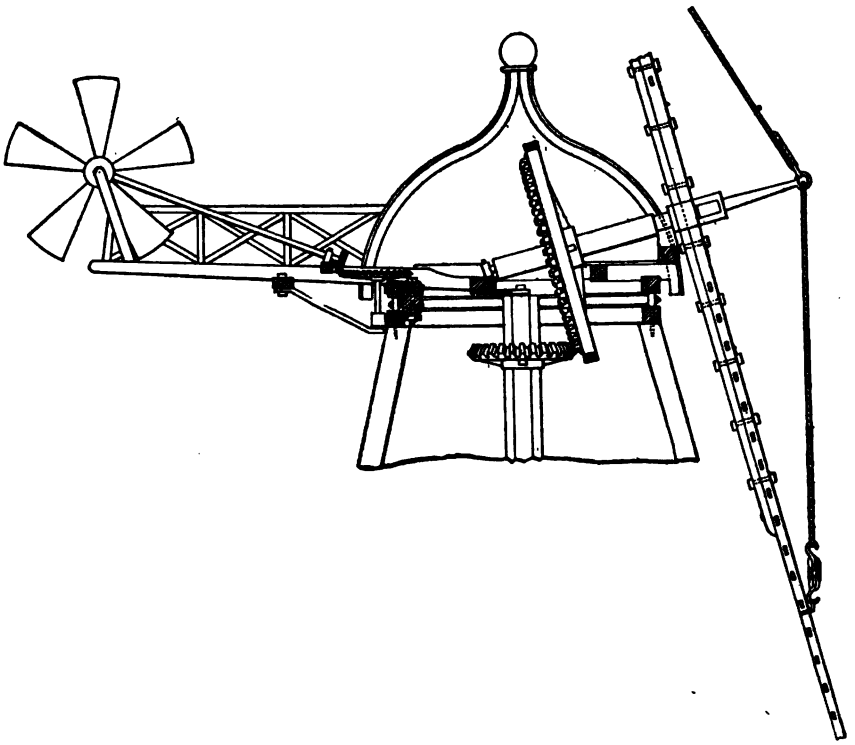
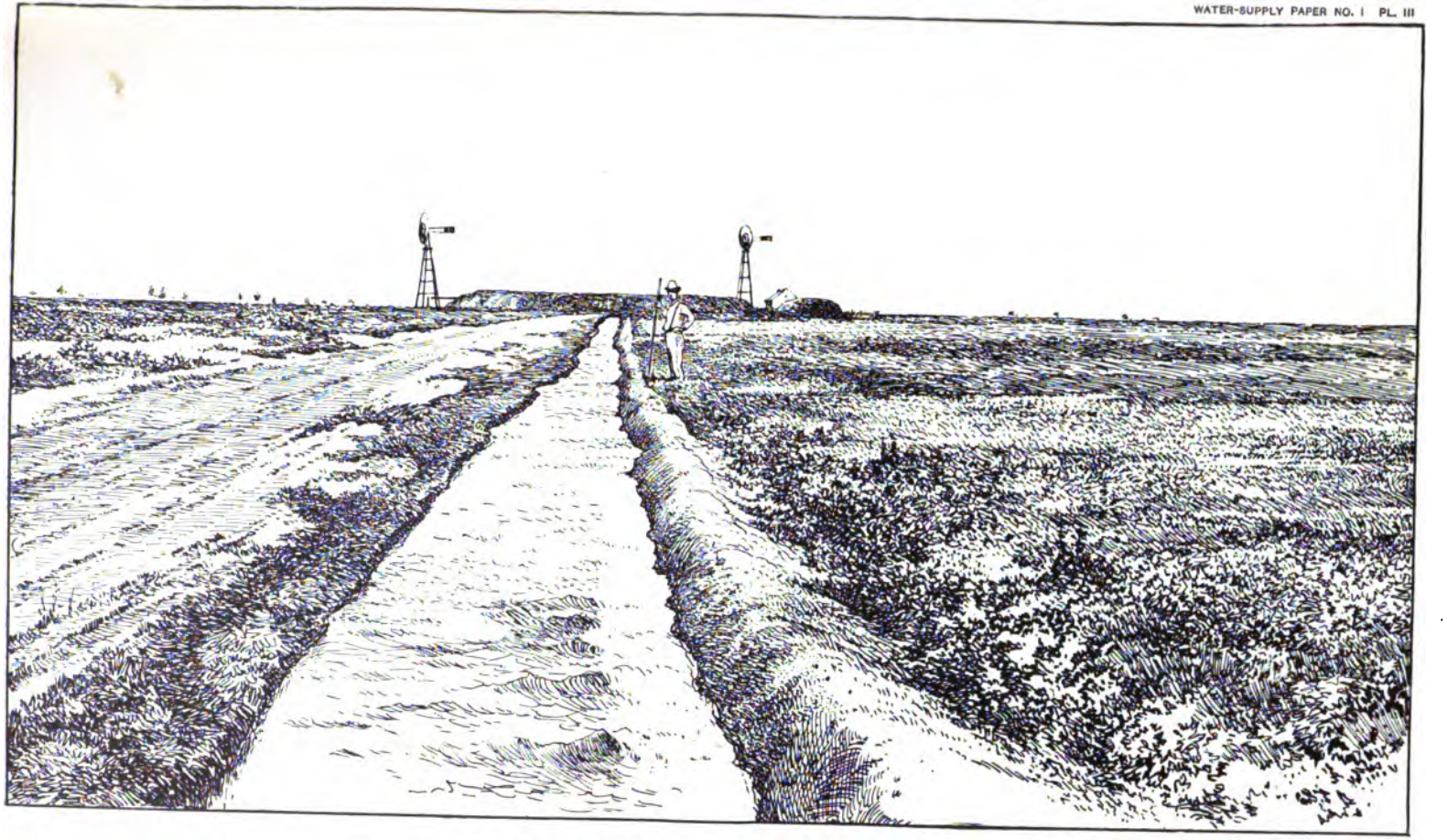


FIG. 10.—Early form of head of tower windmill.

of special types, including various combinations of solid and sectional wheels and those having varying arrangements of rudder. Some of these special types are rudderless, the wind pressure upon the wheel being relied on to bring it into direction.

In selecting a windmill to perform a given duty the irrigator will have many forms from which to choose, and, after a careful perusal of catalogues and circulars furnished by different makers, must use his own discretion in choosing that which seems to best fit his requirements. Below are enumerated a number of the more prominent American windmills. No attempt is made to name them in the order of excellence.



IRRIGATING DITCH AND EARTH RESERVOIR.

Moreover, no attempt is made to present a complete list, many forms of mills being on the market which may be equally as good as those named.

Of side-vane governor mills the Corcoran and Eclipse are excellent examples. Of centrifugal governor mill the Halliday and Althouse are good examples, the latter being folding and rudderless. The Buchanan is a good example of a special form of wheel dependent for its regulation on the tendency of the wheel to go in the direction it turns as the velocity and wind pressure increase. The Stover mill has a solid-sail wheel with vanes so regulated that it may be reefed, stopped, or otherwise controlled to go slowly in heavy winds. The Perkins mill has a solid wheel with metal vanes, and an automatic rudder, which also acts as an automatic regulator. This, like many of the more recent American mills with metal vanes, as the Aermotor, Gem, Crane, and Ideal, is back-geared. The Aermotor is one of the most popular of this class of modern American windmill with steel vanes. The Leffel windmill has metal vanes made on a helical curve, and depends for regulation on the fact that the center line of the wheel shaft stands off from and parallel to the plane of the rudder.

Others of the modern American type of metal-vane wheels are the Cyclone and Woodmanse. The Advance is of the automatic-regulating rudder type, and has both steering vane and governing rudder. The Carlyle is a special type, having a rudder arranged to reef the sail in storms, and so attached by an adjustable cam as to cause the center of gravity of the rudder to rise as the rudder falls toward the wheel.

Drive wells should not, as a rule, be relied on to supply windmills, as the flow of water from such wells is usually limited, because of the small stratum of subsurface water from which they derive their supply. The well should be of ample size and properly lined. It is not infrequently necessary to place the pump down in the well if the depth of this below the surface is such that water can not be successfully raised by suction. The windmill should be placed directly over the well or other source of supply, and on a wooden or iron tower or scaffolding sufficiently high to raise the wheel 20 to 30 feet above all surrounding obstructions. As commonly constructed, this tower is supported on four inclined pillars which straddle the well, and on its top is built a platform or turntable with an open center through which the pump rod descends vertically to the reciprocating force pump in the well. Wooden towers of this form are built from 20 to 40 feet in height, with upright corner posts of 4 by 4 to 4 by 6 inch timbers, crossed-braced with 1 or 2 by 6 inch planks. The corner posts are usually firmly anchored and doweled into foot posts buried in the ground and made of 8 by 8 inch timber. Nailed to one of the side pieces is a ladder by which to reach the platform.

Windmill towers are now often built of angle steel varying in size from 2½ to 4 inches, according to the size of the wheel and height of

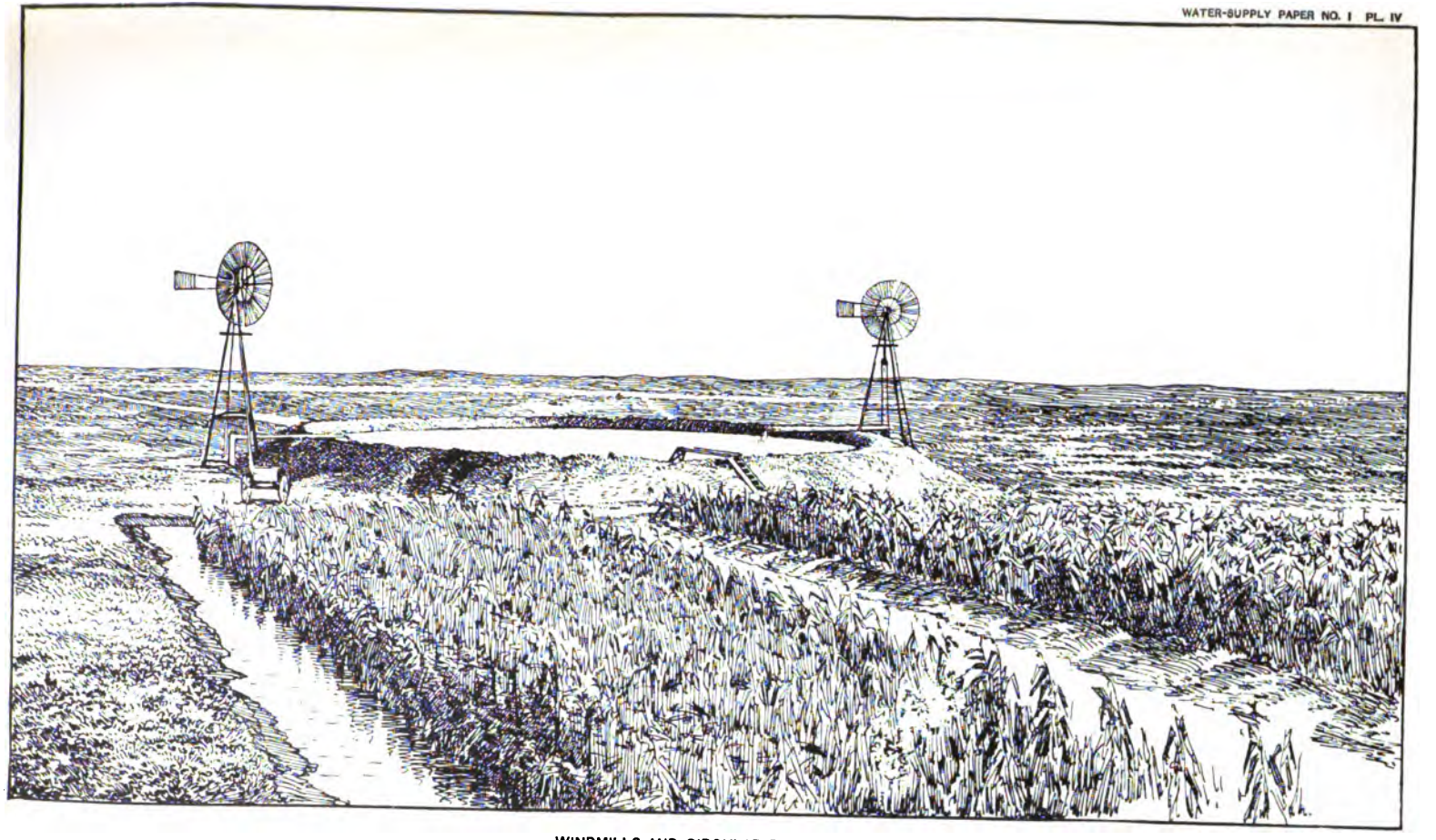
the tower. These are in form more graceful than the wooden towers, and more stable, since they offer less resistance to the wind, and if properly proportioned should outlast wooden structures and withstand heavier gales. In the illustration (Pl. II) one of these towers is shown supporting a tank above which in turn is the windmill, this arrangement being adapted for village or domestic supply, combined with irrigation. In order to secure pressure for the former purpose the water is pumped by the windmill into the vertical pipe leading to the tank, but at the times when it is used for irrigation the water is not lifted to this elevation, but is only brought to a short distance above the ground, being allowed to flow out into an open pond or reservoir from which it can be drawn to the fields.

These steel towers are built as high as 100 feet, and at comparatively little cost, so that there is no difficulty in raising the wind wheel well above all surrounding obstructions. A recent development of interest in the construction of such towers is a tilting tower. This is constructed in such a manner that the upper part carrying the wheel can be tilted or brought down to the ground in a few moments and with little exertion, permitting easy adjustment and oiling. Metal towers are usually anchored on heavy wooden posts, or preferably in masonry, where the latter is easily obtainable.

In erecting either wooden or steel towers care should be taken to keep them plumb and to place the pump rod directly over the pump. Above the platform the horizontal crank shaft is supported in bearings on the upper movable part of the turntable and is connected with the pump by a swivel joint, in order to permit of rotation of the mill top in making necessary adjustments of the sails to changing directions of the wind. An overhanging arm of the crank shaft carries the wind wheel. This, in some forms of mill, is on the lee side of the tower, in which case it maintains its direction perpendicular to the wind by pulling the turntable around, and is rudderless. In other forms the pressure of the wind on a rudder vane of sufficient area and leverage to overbalance the wind keeps it nearly perpendicular to the direction of the latter and on the windward side of the tower. Most mills have, in addition, a controlling or regulating gear by which they can be stopped when the reservoir is full or repairs are necessary, and to prevent damage during gales. This gearing may be either automatic or operated by hand.

There are many varieties of force, siphon, and patent pumps used in lifting water by wind power. It is impossible to say which of these is best suited for general service. The irrigator will do well to leave the selection of the pump required for his particular conditions to the windmill maker, for every manufacturer of windmills is prepared to supply any of the standard pumps and is sure to suggest that type and size which he believes will best meet the requirements, that it may make the best showing for his mill.

Windmills average in cost from $50 to $400, according to size and



WINDMILLS AND CIRCULAR RESERVOIR.

make. Storage tanks or reservoirs may be built for $100 and upward. The pump worked by the wind wheel should be of the best make and of a diameter not less than 3 inches and thence to 8 or 10 inches, certainly of sufficient capacity to handle all the water which the wind wheel is capable of lifting. On an average a 5-inch pump will discharge 250 cubic feet an hour, a 6-inch pump about 380, and an 8-inch pump 650. On this basis, and with the average water duty, a 5-inch pump will therefore irrigate 6 acres if running constantly, or 2 acres if running one-third of the time. The average windmill will irrigate from 1 to 3 acres. If it is supplemented by ample storage facilities these figures may be multiplied by 3 or 4. In other words, it will irrigate from 3 to 10 acres. There are windmills of sufficient size in the West, where the wind is amply steady, to irrigate, with the aid of storage tanks, from 5 to 10 acres, pumping from wells 30 to 150 feet in depth. Theoretically, a 25-foot windmill working eight hours a day for one hundred and twenty days will pump 40 acre-feet to an elevation of 25 feet, and if storage capacity for half this volume be provided it will be capable of irrigating about 20 acres.

An excellent example of a windmill pumping plant is that of Mr. E. E. Frizell at Larned, Kansas, shown on Pl. III. This consists of three 14-foot steel windmills on 30-foot towers and discharging into a reservoir 130 feet in diameter, with banks 8 feet high. The pumps have 10-inch cylinders, and with a lift of 25 feet can fill the reservoir in about two days. The available capacity of the reservoir is nearly 2 acre-feet (Pl. IV), and in a season the plant is capable of irrigating 60 acres successfully. When the reservoir is filled a sufficient head of water is available to enable it to flow freely over any part of the irrigable area and in sufficient volume to thoroughly soak the soil.

WATER WHEELS.

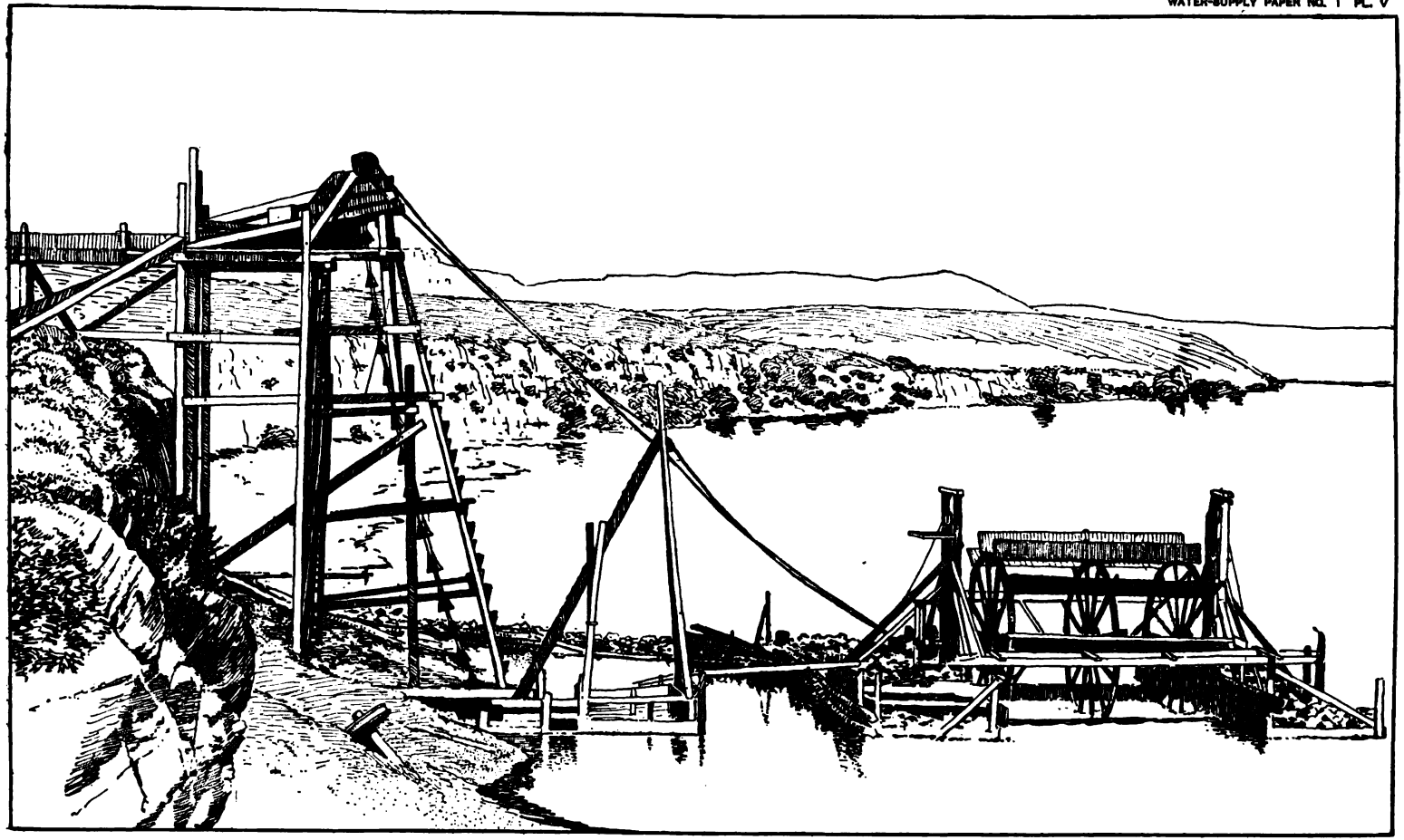
Water acts as a motive power by its weight or by its impulse. In the former case it falls slowly through a given height, and in the latter it passes through the motor with a constantly increasing velocity. Water motors may be divided into two classes, (1) water wheels and (2) water engines, each of which may be subdivided into several classes. Of water wheels the principal varieties are (1) undershot wheels, (2) breast wheels, (3) overshot wheels, (4) Pelton wheels, and (5) turbines. In addition there are water-pressure engines, rams, bucket engines, etc., but most of these are antiquated or not economical, and it is therefore hardly necessary to describe them as machines for elevating water for use in irrigation. Of these devices, however, rams are very economical where but a small volume is to be lifted.

In considering the subject of lifting water by means of water power, it may be said, as of other water-lifting machines, that the duty they have to perform may be the raising either of a large volume of water

to a small height or of a small volume to a large height. These duties may both be performed with a water power derived through either a large volume of water from a small height or a small volume of water from a great height. It is this intimate connection between volume and head of power and resulting work which calls for the exercise of discretion on the part of the irrigator in choosing the water motor best suited to his special requirements. A ram is nearly always called upon to utilize a large volume from a small height to raise a small volume to a great height. The Pelton water wheel generally utilizes a small volume from a great height to elevate varying volumes to varying heights. Undershot and breast wheels utilize large volumes from small heights to elevate moderate volumes to small heights.

Of undershot water wheels there are practically three varieties—midstream wheels, the common undershot wheel, and the Poncelet wheel. The midstream wheel is actuated by the velocity or impulse of a current of water in the middle of a broad stream in which it may be set. Such wheels are rarely employed, but when they are it is almost exclusively to raise water for irrigation. They are simple in construction and operation, and may be advantageously employed where water is abundant, even in streams having moderately low velocity. Such wheels produce the best result when their float boards or paddles are made straight, but not radial. They vary from 12 to 25 feet in diameter, their float boards varying between 10 and 15 in number, 2 of which should always be immersed at the same time. These project from 24 to 30 inches from the wheel rim, dipping into the water about one-half their depth. In rivers, the water levels of which fluctuate, the axle of the wheel is placed on movable supports, as shown in fig. 11, to render it capable of being raised or lowered at pleasure. An interesting adaptation of the midstream wheel for lifting water for irrigation is that illustrated on Pl. V, which represents such a wheel floating in the Colorado River, and by means of gearing and an endless cable, causing buckets attached to an endless chain to lift water from the river to the irrigating ditch above, a height of about 25 feet.

Numerous midstream wheels have been employed in the West for pumping irrigation water. They are almost always used as norias, having attached to their outer rims a number of buckets which dip into the water as the wheel revolves, and, as they reach the upper portion of their cycle, spill their contents into a trough which leads into the irrigation ditch (Pl. VI). Such wheels are of very ancient origin, having been used in almost every country in the world, most extensively, perhaps, in Egypt and Italy. Some very large wheels of this variety have been successfully employed on the Green River in Colorado. The diameters of these wheels are from 20 to 30 feet; they are hung on wooden axles 5 inches in diameter, and their paddles dip 2 feet into the stream. The buckets attached to their outer circumferences are of wood, having an air hole in the bottom closed by a suitable



MIDSTREAM WHEEL DRIVING A BUCKET PUMP.

leather flap valve. These buckets are 6 feet in length and 4 inches square, and have a capacity of two-thirds of a cubic foot each. The largest of them raises 10 cubic feet per revolution, and handles in all about 4,000 cubic feet per day, or, approximately, one-tenth of an acre-foot. An apparatus not unlike the noria is the ancient wheel employed in Egypt and known as the tympanum (Pl. VII). This wheel is a common undershot wheel turned by paddles dipping into a flowing stream, but instead of lifting water in buckets, the water enters a series of spiral gutters, and as the wheel revolves flows through these until it finally reaches the center of the wheel near the hub and passes out at this point into the irrigation ditch.[1]

Common undershot water wheels are better than midstream wheels where a fall of sufficient height to give a good velocity can be obtained. These are placed in a channel or mill race of about the width of the wheel, but a little wider at the inlet than at the wheel. The paddles

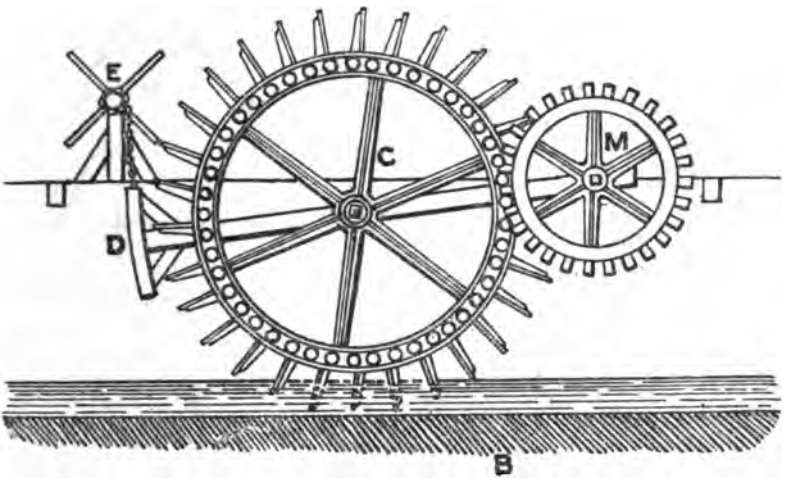


FIG. 11.—Undershot water wheel.

are similar to those of midstream wheels, though they are sometimes curved and of iron (fig. 11). They vary in diameter from 10 to 20 feet and have usually from 30 to 40 paddles of from 1½ to 2½ feet in depth and with face lengths of from 2 to 6 feet. In the illustration, fig. 11, a simple form of undershot wheel is shown, diagrammatically, exhibiting a common method by which the wheel can be raised or lowered to suit the fluctuating height of the stream. The axle of the paddle wheel (C) is supported at about the middle by heavy timbers (D), the ends of which on the downstream side are pivoted in line with the axle of the wheel (M), which transmits the power. The upstream ends of the timbers are hung on chains passing over a windlass (E), by which the timbers can be hoisted or lowered, thus adjusting the height of the paddles. Greater

[1] A form of wheel similar to this, carrying the water through curved pipes instead of rectangular compartments, is illustrated in the Scientific American of September 5, 1896, page 17.

efficiency can be obtained from undershot wheels if the paddles are made concave or of the type known as Poncelet. These latter are immersed nearly to the height of their axle, the water being partially screened from them by a curved breast-piece or apron, so that the current impinges against the curved blades somewhat in the manner of the action in a turbine.[1]

Overshot wheels are economical in their use of water, and are therefore employed where it is scarce. In these the water is delivered above

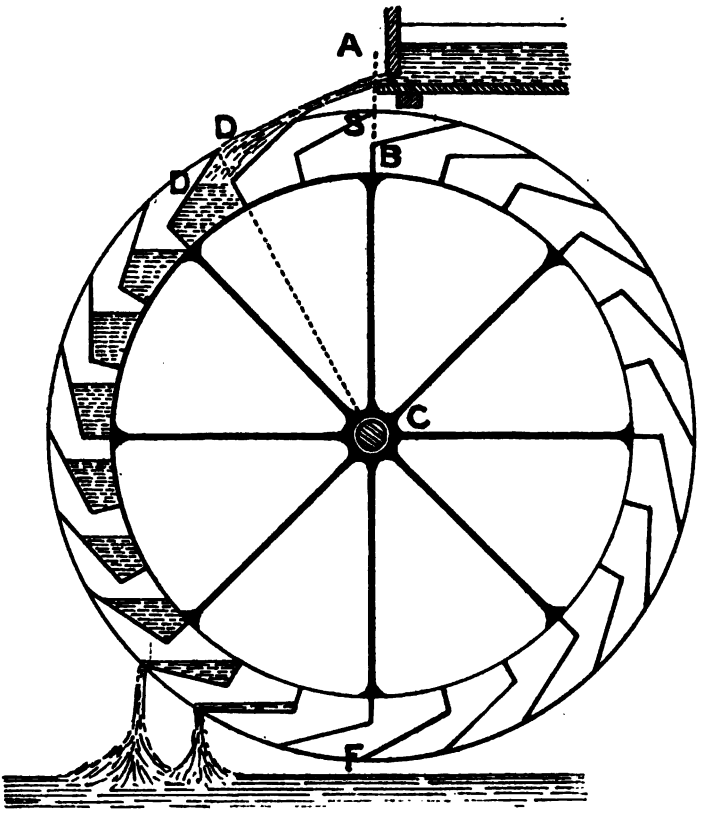
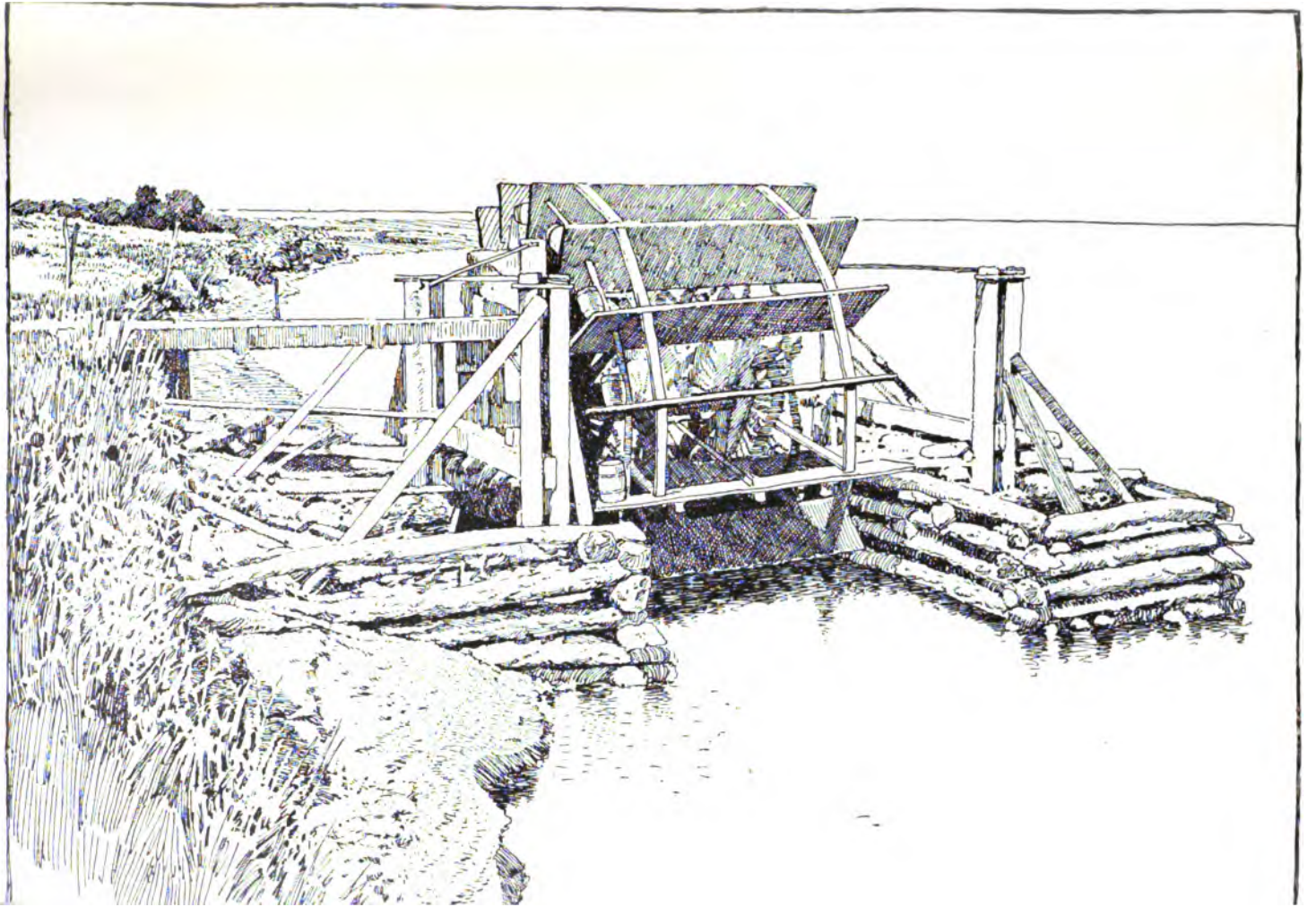


FIG. 12.—Overshot water wheel.

the wheel by means of a flume, mill-race, or penstock, and they are so constructed that the water may be thrown upon either the near or the far side of the wheel, according to the arrangement of the outlet gates controlling the supply. On the outer circumference of the wheel is a series of buckets of the full length of the wheel face. Into these buckets the water pours, and by its weight carries the wheel down, causing it to revolve (fig. 12). As it turns, each bucket (D D) fills in passing the

[1] The Mechanics of Engineering and of Machinery, Weisbach and Dubois, Vol. 2; John Wiley & Sons, 1889, page 316.



inlet orifice (A) and empties as it approaches the outlet channel, so that on one side are always a certain number of filled buckets. Such wheels may be employed to utilize falls of from 6 to 60 feet. In order to lose as little of the fall height as possible, the bottom of the wheel should approach close to, but not dip into, the lower water surface. The greater the width of the faces of these wheels the larger volume will their buckets hold, and, accordingly, the greater power will they exert. Overshot wheels may be employed to operate, through gearing or belting, any of the usual forms of reciprocating, centrifugal, or force pumps, and they will elevate volumes of water to heights proportional to the power which they are capable of developing. The largest, and therefore, perhaps, the most interesting, overshot wheel ever constructed is on the Isle of Man. The diameter of this wheel is 72 feet and 6 inches, and it is claimed to develop 150 horsepower, which is transmitted several hundred feet by means of wooden trussed rods to a series of pumps capable of raising about 33 cubic feet of water per minute to a height of 1,200 feet.

Turbines are horizontal water wheels and may be classified according as they are acted upon—(1) through impulse, (2) through pressure, or (3) through reaction. Impulse wheels have plane or concave vanes or float boards on which the water strikes more or less perpendicularly. Pressure wheels have curved float boards along which the water glides. Reaction wheels are actuated by an arrangement of pipes from which water issues tangentially. To this latter class belong Pelton and other forms of tangential wheels. Pressure and reaction wheels, though similar in construction, differ in that in the former the passages between the vanes are not completely filled with water, while in reaction wheels the water fills and flows through the whole section of the discharge pipe. Turbine wheels are again subdivided into the following three classes: (1) outward flow, (2) inward flow, (3) mixed or parallel flow, the latter really combining the first two classes. Outward-flow turbines receive the water at the center and deliver it at the periphery of the revolving wheel. Inward flow turbines act in practically the reverse manner from that of outward-flow wheels.

Turbines possess an advantage over the older types of wheels in that they may be used with any fall of water, from one to several hundred feet. They have many other advantages over such water wheels; they may be regulated according to the power required and the water supply available, the regulating apparatus being such that the efficiency remains nearly the same, whether water is scarce or abundant. Again, turbines may be submerged, while other forms of water wheels must be elevated above the tail-race. The turbine takes its supply at the bottom of the fall, while overshot water wheels take it from the top of the fall, thus the former utilizes practically the whole height of fall. Furthermore, turbines move with a greater velocity than vertical water wheels, and hence may be materially reduced in size and weight for an equal

production of power. In fig. 13 a turbine is shown geared to a centrifugal pump, as employed in irrigation.

There are a number of successful forms or types of turbine water wheels made in this country. The advantages of each of these are fully described in the trade catalogues of the various makers, and much additional useful information relative to them can be obtained by the prospective irrigator through correspondence with the manufacturers. In the West are a number of irrigation pumping plants operated by turbines. The wheels range in size and power from a few inches in diameter, operated under but a few feet of head, and developing a fraction of a horsepower, up to enormous engines rivaling those recently built for utilizing the fall of Niagara, capable of producing as much as 2,000 horsepower each, and operated under several hundred feet of head, their

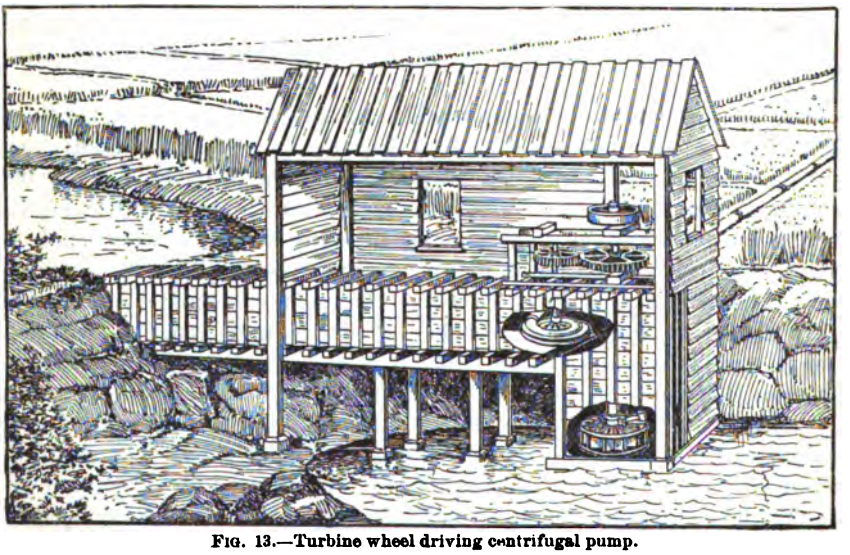
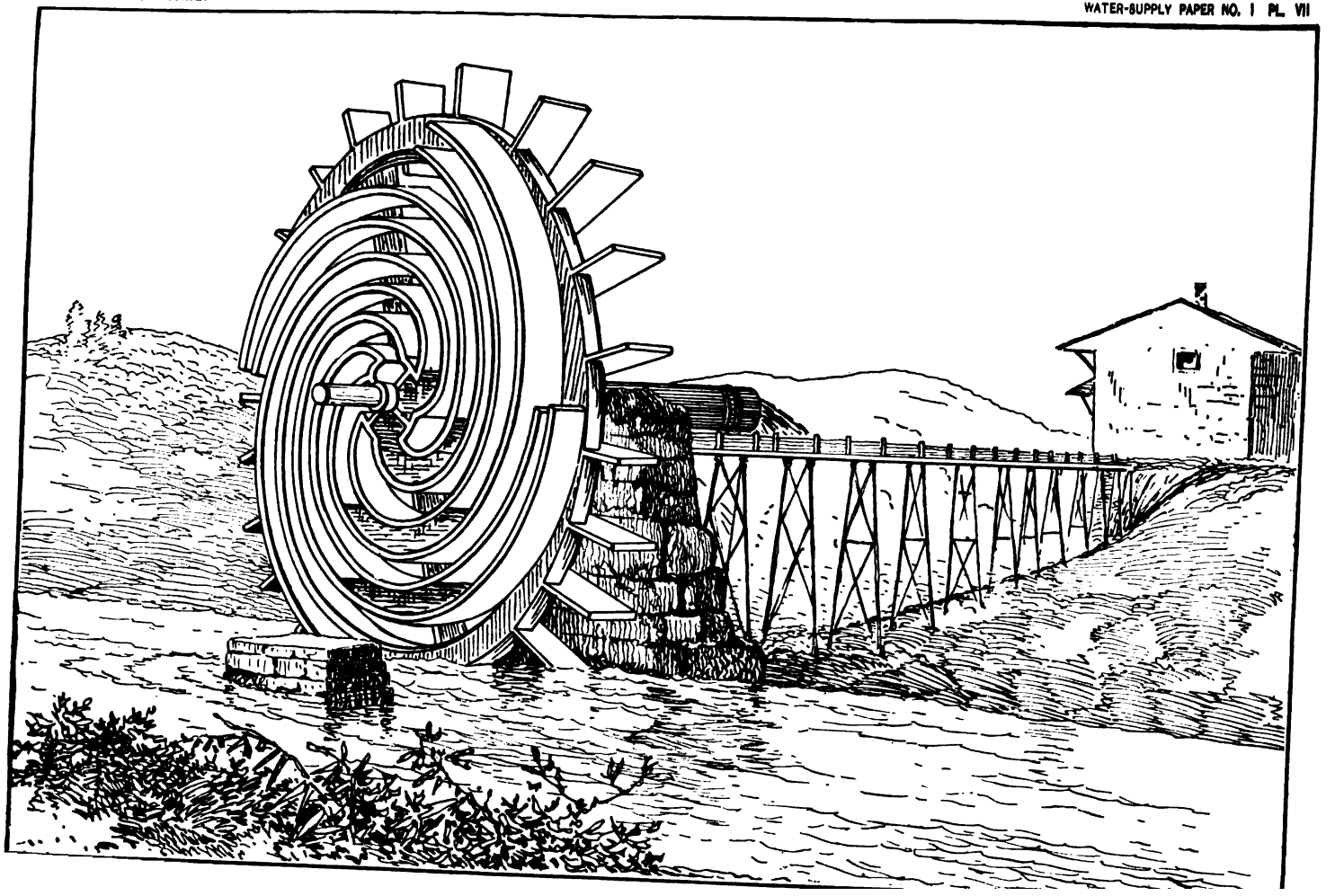


FIG. 13.—Turbine wheel driving centrifugal pump.

diameters being as great as 6 to 8 feet. They range in price, likewise, from $100 to several thousand dollars. There has been recently erected at Prosser Falls, Washington, a turbine power and pumping plant capable, it is estimated, of irrigating 4,000 acres besides furnishing power for factories and other purposes. This plant pumps water to an elevation of 100 feet, with a power-producing fall of 20 feet. There are two turbines, each 48 inches in diameter, and each capable of developing 135 horsepower under a 12-foot head. Each operates a duplex pumping engine of 25-inch cylinder and 24-inch stroke, each having a capacity of 4,000 gallons a minute.

Tangential water wheels are simpler in construction than turbines, less liable to get clogged or out of order, and they may be worked under much greater heights of fall than other forms of water wheels. They derive power from the impulse of water discharged from a nozzle



at buckets on the lower side of the wheel (fig. 14). They do not work so satisfactorily as turbines with heads less than 30 feet, though they produce small powers with great efficiency at even lower heads. But above 50 feet and up to 2,000 feet there is no other water wheel so efficient as the tangential. It has a wide range of adaptability to varying conditions of water supply by simply changing the nozzle tips. As the buckets are open, there is no uncertainty from derangement of parts or stoppage by driftwood. They are relatively cheap of installation, and admit, by varying their diameters, of being placed directly on the crank shaft of power pumps without intermediate gearing. The Pelton is the most common form of tangential wheel.

Few Pelton wheels have yet been employed in pumping water for irrigation, but as they become better appreciated it is probable that their value in utilizing small volumes of water from great heights will

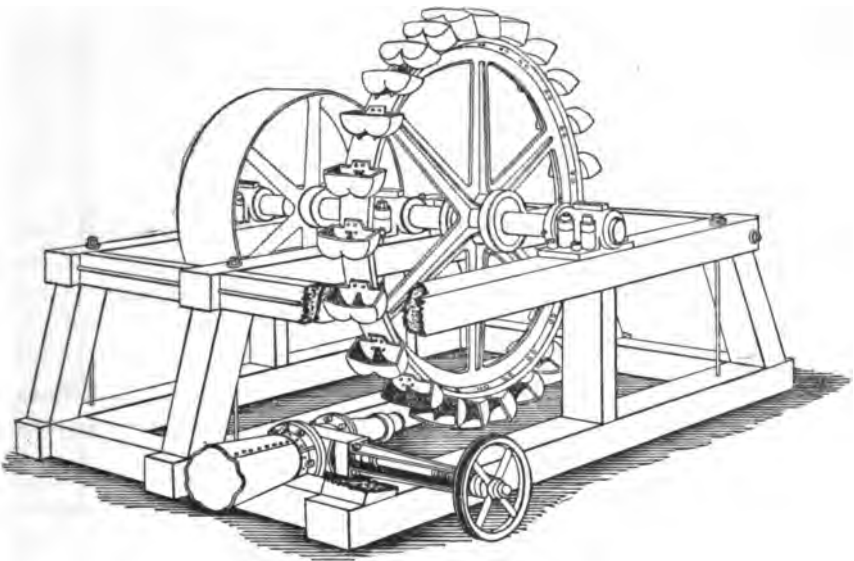


FIG. 14.—Pelton water wheel.

render them more popular. Pelton wheels are made of varying sizes, from those capable of developing a fraction of a horsepower from the water supply of a house faucet or mountain spring to the largest size. That recently constructed for the North Star Mining Company, Grass Valley, California, operated under an effective head of 750 feet, is 18½ feet in diameter and of 300 horsepower capacity. This wheel is mounted on a bicycle-spoked frame having a 10-inch steel shaft. Its peripheral speed is 6,000 feet a minute, and its efficiency is about 90 per cent. Another Pelton wheel working under 810 feet head is but 40 inches in diameter and develops 600 horsepower.

There is now being made by the Austin Manufacturing Company, of Chicago, an apparatus called the Improved Current Motor, the object

of which is to develop power from the water flowing in a large stream something in the manner in which it is developed by the ordinary undershot water wheel. This apparatus consists of a narrow, floating, scow-shaped pontoon, a sort of floating platform, about 100 feet in length by 11 feet in width. The upstream end of this is pointed like the prow of a boat, that it may part the current of the stream. This float is anchored in midchannel and carries a couple of endless chains running over sprocket wheels 5 feet 6 inches in diameter hung on 2-inch shafts. These sprocket wheels are situated at each end of the pontoon, and the endless chains bear between them, at intervals of 8 feet, float boards 6 feet 10⅜ inches in length by 3 feet in depth. These float boards are acted upon by the current, which carries them along beneath the pontoon, over the rear sprocket wheel, whence they return above the plat-

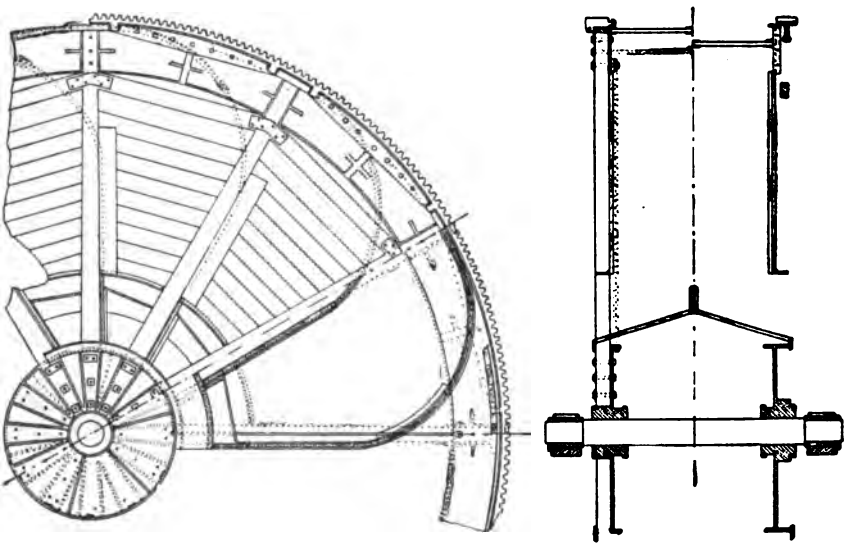


FIG. 15.—Wheel for lifting water on Chesapeake and Delaware Canal.

form to the front sprocket wheel and again pass into the water. The power developed by this motor is transmitted by belting and gearing to an ordinary endless chain carrying buckets or other mechanical water elevators (see p. 51) which lift the water from the stream into the irrigating canal.

A curious and at the same time interesting form of water wheel, which is not a water motor, but is used to lift or pump water, is one which is employed on the Chesapeake and Delaware Canal to elevate water from a lower to a higher level. This wheel (fig. 15) is similar in its mode of operation to the tympanum of Egypt, shown on Pl. VII. It is 39 feet in diameter, 10 feet in width on the outside, and 7½ feet on the inside. Of its face width 24 inches is occupied by two bands or rows of heavy iron cogs, which bind the outer edges of the wheel.

This revolves on a 15-inch iron axle, reduced at the bearings to 12½ inches, and is turned by a couple of cogged pinions, each 4 feet in diameter, mounted on a 12-inch crank shaft. These pinions gear into the cogged bands on the outer edges of the wheel. The shaft bearing the cogged pinions is connected directly, through cranks, with two large low-pressure condensing beam engines. These engines have each 7-foot stroke and 36-inch cylinders, and are each capable of developing 175 horsepower, or a total of 350, on a consumption of 900 pounds of coal per hour. The central portion of the wheel, 8 feet in width on the face between the cogged bands, is divided into twelve openings, each about 18 inches wide at the mouth, and these are the entrances to spirally curved buckets of the full width of the wheel, which enlarge as they approach the center and then diminish at their inner or discharge orifices to a width of 2 feet. Surrounding the main axle is a conical wooden hub, from 8 to 11 feet in diameter, so designed that the water falling on it from the buckets is thrown in either direction and empties into two canals, one leading away from each side of the wheel, discharging a little beyond into the main canal. The buckets terminate within 4 feet of this central hub, and have an inside depth along the diameter of the wheel of 12 feet. As the wheel revolves, the buckets fill by immersion in the feeder canal, and the water falls out at the lower end of these buckets onto the hub and thence into the out-take canals. The lift from the surface of the feeder canal to the surface of the out-take canal is 14 feet. The wheel makes 100 revolutions per hour, and is capable of lifting 300,000 cubic feet of water per hour to this height. This is equivalent to about 170 acre-feet of water per day of twenty-four hours, or about 83 second-feet flowing continuously. This, on a consumption of about 10 tons of coal for twenty-four hours at $5 per ton, or $50, is equivalent for fuel alone to a charge of about $1.30 per acre-foot. The efficiency of this machine seems to be relatively so high as a pumping machine for low lifts and large volumes that it is not improbable that it may be found advantageous to employ some such apparatus in irrigation.

Hydraulic rams may be utilized where there is a trifling fall and but a small amount of water is to be lifted. They work on the principle of a large volume of water having a small fall forcing by impulse blows a smaller volume to a higher elevation. Water is delivered to the ram from a reservoir or stream with steady flow through the supply or drive pipe. At the end of this is a check valve, opening into a chamber connected with the discharge pipe. As the water passes through the drive pipe it flows, with a velocity due to its height of fall, through a weighted pulse or clack valve which opens inward. It almost instantly closes this valve, and at the moment the issue of water ceases a ramming stroke is created which opens the delivery valve and permits the water to enter the air vessel, and at the same time, because of its velocity, the water flows back through the drive pipe. At the instant the backward flow begins the delivery valve closes and the pulse valve opens

to allow the passage of the water from the supply pipe, and the operation is repeated. In general, it may be stated that a hydraulic ram will elevate one-seventh of the supply volume of water to a height five times the fall, or one-fourteenth part to ten times the height of fall. The fall should range from 2 to 10 feet, but not more. Hydraulic rams are very cheap, both to purchase and to maintain, and are unaffected by tail water, as they will continue working even when flooded. It may be stated that in placing a hydraulic ram the length of drive pipe should be increased as the height to which water is lifted is increased, so that water shall not be forced back in the drive pipe as the pulse valve closes. The length of the drive pipe should in general be five to ten times the height of fall. The delivery pipe is usually from one-third to one-fourth the area of the drive pipe.

Of the many types of hydraulic rams in the market but few are of

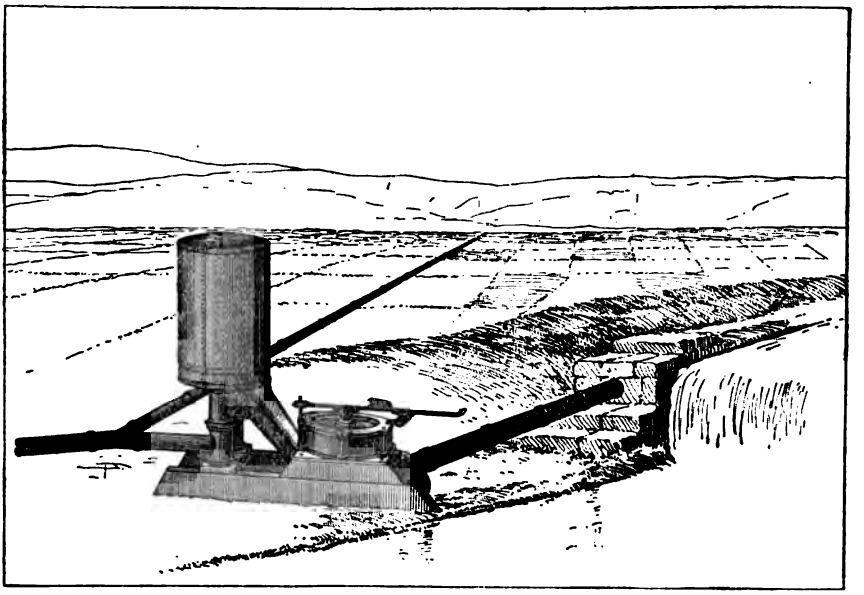


FIG. 16.—Hydraulic ramming engine.

sufficient capacity to perform the amount of work required in supplying irrigation water. Those which are capable of performing this work partake chiefly of the nature of hydraulic ramming engines, and are constructed somewhat differently from rams proper. They may be actuated by dirty as well as clear water, but are more intricate in their construction than are simple rams. One of the most effective of these engines is the Rife hydraulic ramming engine (fig. 16). This is said to be capable of elevating water to a height of 25 feet for every foot of fall, and to deliver one-third of the water used in operation to two and one-half times the height of fall, or one-sixth of the water to five times the height of fall. Only the largest of these are capable of elevating enough water for irrigation. Those having a drive pipe 8 inches and a

delivery pipe 4 inches in diameter are capable under a head of 10 feet of elevating about one-half of an acre-foot per day of twenty-four hours to a height of 25 feet. Such a machine costs $500, or at the rate of about $10 per acre irrigated.

HOT-AIR AND GASOLINE PUMPING ENGINES.

These machines have been extensively used in the East for pumping moderate quantities of water for domestic consumption and for small factories or villages. Lately they have been successfully employed in pumping small irrigation supplies in the West, and are undoubtedly destined soon to gain popular favor, chiefly because of their simplicity, economy, and the ease with which they can be stopped and started and maintained in successful operation by unskilled labor. Hot-air pumping engines do not depend for their operation on power developed by the expansion of steam to convert heat into motion. Gasoline engines are likewise operated without converting the heat into steam, but by the expansive force produced by the explosion of vaporized gasoline when ignited in contact with air. Both of these types of engines are made only to develop comparatively small powers, and therefore are utilized in pumping but comparatively small volumes of water, usually irrigating from 5 to 50 acres. These engines have decided advantages over water and steam motors in that they can be employed where there is not sufficient water supply to operate a water motor and because of the kind of fuel which they consume, gasoline engines being serviceable in arid regions where fuel is expensive and difficult to obtain, and hot-air engines being capable of utilizing almost any variety of fuel. Moreover, these engines are small and compact, simple of erection by comparatively unskilled labor, and may be operated with the minimum expense for supervision and with little skill on the part of the operator.

Hot-air engines are constructed almost wholly for pumping purposes, the motive power and pumping apparatus being combined in one machine inseparably connected in one frame. They are so simple in operation that anyone capable of lighting a match may run them. There is no possibility of explosion, and when once started they require no further attention than for replenishment of fuel. They are made in capacities ranging from a few gallons per minute to one-tenth of a second-foot, equivalent to two-tenths of an acre-foot per day of twenty-four hours, limited by the height of lift, which varies from a few feet to 500 feet. The chief objection to hot-air pumping engines is their great first cost, which for the larger size is $600, or $6,000 per second-foot, equivalent to about $100 per acre irrigated.

Gasoline engines are used extensively in some portions of the West, notably in Kansas, for pumping water for irrigation. They are made of various dimensions, up to those capable of developing 50 horsepower and pumping a correspondingly large volume of water, and they are

constructed as combined motive and pumping plants or as separate motors to be attached to varying forms of pumps. The chief advantages which these machines have over other motive powers for pumping are their compactness and simplicity of installation and operation, and, above all, their cheapness, not so much for first cost as for ultimate maintenance, though in this latter item they do not surpass hot-air pumping engines. The largest of these engines are capable of elevating for low lifts as much as 3 second-feet of water, or 6 acre-feet per day of twenty-four hours, and lesser quantities to greater heights in proportion. The cost of operation of such a machine as this has been asserted to be for gasoline as low as $1.25 per day, or 20 cents per acre-foot. It is stated that these engines will pump water at a cost of about 1 cent per hour; and working ten hours a day, the largest size will elevate sufficient water to a height of 20 feet to irrigate about 320 acres if storage be provided. The first cost of the plant is from $400 to $600 for engines capable of irrigating 10 to 20 acres, and larger plants in proportion. This is at the rate of about $30 per acre without storage, and the cost of operation is about $1.25 per acre irrigated.

STEAM PUMPING ENGINES.

Of the many forms of motors utilizing steam power, the following two classes cover most of those which are of interest to irrigators: (1) those which utilize steam power by indirect transmission to the pump through gearing, belting, or other separable connection; (2) those which utilize steam power through an engine directly coupled with the pump, as direct-acting or fly-wheel pumping engines. It is not desirable to refer here to the many forms of steam engines and boilers employed in developing steam power for actuating plunger, centrifugal, or other pumps. They are innumerable and are manufactured in all varieties, forms, and sizes and at all prices. The irrigator must determine by consultation with makers of steam engines and boilers those which are best suited to the work which he has to perform. On the other hand, direct-acting engines, being inseparable from their pumps, may be here considered, as each differs not only in its motive power but in its pumping mechanism.

In endeavoring to determine the power required of a pump that it may elevate a given volume of water to a given height the same considerations must be dealt with as in transforming power developed by windmills or water motors into volumes lifted to given heights. This may be roughly stated by the formula: horsepower required, H. P., equals time of work in minutes, t, multiplied by volume of water in cubic feet, v, multiplied by weight of a cubic foot of water ($62\frac{1}{2}$ pounds), w, divided by 33,000 pounds, the result to be multiplied by the height to which the water is elevated in feet, h, plus the resistance due to friction in pipes, f.

$$\text{H. P.} = \frac{62\frac{1}{2}\, t\, v}{33{,}000} \times h + f$$

The frictional resistance to flow is an indefinite quantity which may

be most easily determined by reference to such tables as Trautwine's or others giving fractional resistance for pipes of given diameters and lengths.

Direct-acting steam pumping engines differ from other steam pumps in that the motor and pump are combined inseparably in one mechanism, the power which performs work being derived from an ordinary steam boiler, not through an engine separately geared or belted to the pump, but directly from pump plungers which form part of the steam piston or connecting rod. Such direct-acting pumping engines may be either single or double acting. They have the water and steam ends centered in one line, so that the water plunger and steam piston are attached to the same piston rod and work together without an intervening crank or other connection. This is the simplest and most compact form of steam pumping apparatus, and is more extensively used for pumping than all other varieties of pumping machinery combined, though it is, perhaps, one of the most wasteful and expensive forms of steam engines. It is undoubtedly the most substantial and satisfactory form of steam pumping apparatus for lifts exceeding 20 feet, for it is less liable to derangement or accident and better fitted to perform constant, hard work than any of the separable steam engines and pumps. Machines of this class are manufactured by many establishments, and the qualities and efficiencies of the various makes are well established by competition and experiment. Steam pumping engines are similar in nearly all the various makes, differing chiefly in details of valve motion. Among the best of these are the Knowles, Blake, Smith-Vaile, Dean, Cameron, Worthington, and Davidson valve movements.

In selecting steam pumping engines, among the points most desirable are strength and simplicity of working parts, large water-valve area, long stroke and ample wearing surfaces, continuity of flow, simplicity of adjustment and repair, and moderate steam consumption. In choosing from the various makes of pumping engines it is well in corresponding with their makers to inform them, among other points, of the purposes for which they are to be used, height of lift and height to which water is to be forced, quantity of water to be elevated, motive power, and quality of fluid, as clear or muddy.

Direct-acting steam pumping engines may be either high-pressure or compound. The latter are economical in both fuel and water consumption, and their cost for operation is correspondingly less, though their first cost is a little greater. The best form of direct-acting are the duplex pumping engines, consisting of two direct-acting steam pumping engines of equal dimensions, side by side on the same bed-plate, with a valve motion so designed that the movement of the steam piston of one pump shall control the movement of the slide valve of its opposite pump so as to allow one piston to proceed to the end of the stroke and come to rest while the other piston moves forward on its stroke.

All single-acting pumps should be provided with air chambers.

These are often an improvement even to double-acting pumps, for though the latter have a fairly steady discharge, the air chamber insures almost perfect uniformity of delivery. The capacity of an air chamber for a pair of double-acting pumps is about five or six times the combined capacities of the water cylinders, while for a single-acting pump it may be ten or twenty times greater. The air chamber performs practically the office of a stand-pipe attached directly to the pump. It neutralizes the variations of velocity of discharge in the delivery pipes, the fluctuations of which might cause danger of ramming and wastage of work. The air chamber obviates this by permitting the excessive delivery of water from a pump stroke to enter it and thus compress the air, while on the return stroke the expansion of the air forces out water to supply the deficiency.

Several extensive steam pumping plants have been employed in the West for providing water for irrigation. The first cost is usually a little greater than for centrifugal pumps, though not always so, depending upon the height of lift. Their efficiency is usually quite high as compared with all other forms of pumping plants, and their maintenance cost is usually less than that for centrifugal pumps. Their operation requires skilled labor, as does that of centrifugal pumps; but they are less liable to get out of order, and any injuries sustained can usually be readily repaired.

In Arizona is a high-pressure pumping engine capable of irrigating 100 acres per season which cost when erected $1,000, or $10 per acre irrigated, while the cost of running it is but $5 per acre. A larger and more modern plant operated near Tucson consists of two compound Smith-Vaile pumping engines, capable, it is claimed, of irrigating 600 acres per season at a cost for operation of $3 per day, the first cost for this plant laid down having been $4,200, and the height of lift being 70 feet. Still another pumping plant, consisting of an automatic cut-off condensing engine with two 150-horsepower boilers, has been erected on the Yuma River. The pumping engine has 18-inch stroke and 42-inch cylinders, and is of 165-horsepower capacity. This is an Allis pumping engine, having a fly wheel weighing 7 tons and making 67 revolutions per minute, the capacity of the pump being 12 second-feet, or about 24 acre-feet in a day of twenty-four hours. This pump delivers water through a 26-inch redwood stave main, elevating the water 80 feet, and this is stored in a reservoir having 23 acre-feet capacity. A year's test of this engine, according to the claims of the owners, shows it to be capable of discharging 12 second-feet at a cost of $3 per second-foot for fuel.

There has recently been erected at Eureka, Kansas, a pumping plant for the irrigation of about 3,000 acres. This consists of two horizontal return tubular boilers and two compound, duplex, direct-acting steam pumping engines of a maximum capacity of 530,000 cubic feet, or about 12 acre-feet per day of twenty-four hours, equivalent to 6 second-feet,

with a total lift of 65 feet. The cost of this plant, exclusive of the storage reservoir, was about $8,000, while the cost for operation is estimated to be $1.60 per acre, assuming that the full area is covered.

In addition to the better-known forms of steam pumping engines, there have been built a number of patented types of pumps, gotten up with the special view of lifting large volumes of water to small elevations for use in irrigating or in draining lands. Three of the more notable of these are the Huffer and Nye irrigating pumps, formerly made in Colorado, and the Menge irrigating and drainage pump, made in New Orleans. The Nye pump is a curiously compact affair, worked directly from a steam boiler in such manner as to utilize atmospheric pressure in producing power through condensation of steam. It requires little steam pressure except for lifts above those made by an atmosphere, say over 25 feet at sea level. It consists of two large cylinders fastened vertically on one bed-plate. Steam is let into one of these and is instantly condensed by a spray of water, thus creating a vacuum or suction power nearly equal to atmospheric pressure, and the cylinder is filled with water. As one cylinder is being filled the other is being emptied, and at the same time receives steam for a similar condensation and vacuum. The action of the steam valves is automatic, and steam enters but one cylinder at a time. These engines have no pistons or packing to wear out and practically no loss of power by friction; they are simple in construction and erection, and little skill is required in placing or in operating them. They are made of varying sizes, the largest being capable of lifting nearly 7 second-feet of water to an elevation of 20 feet, and costing about $1,000, equivalent to a first charge for plant of about $140 per second-foot.

The Huffer pump works on a principle similar to that of the Nye pump, but while the latter is capable of forcing water to a height of nearly 100 feet by direct steam pressure, the Huffer pump is merely an atmospheric lifting pump, capable of raising water only to such height as the aid of atmospheric pressure will permit. The largest sizes of this pump are capable of lifting about the same volume of water as are the Nye pumps. Neither of these pumps has met with popular favor, chiefly because they are not economical motors. In consequence, their manufacture has been discontinued.

The Menge pump has been most extensively employed in pumping water from swamp lands or in lifting water to flood cranberry and rice swamps. Only recently have any of them been used for irrigation, and then only for low lifts, usually between 5 and 10 feet. Above the latter height a two-story or double lift may be employed, but is not quite so economical. For the lower lifts which are within the power of one pump this machine is considered one of the most economical made. It is a combination of wood and metal, and is operated by a stationary engine, belted to a pulley on a vertical shaft set in an upright wooden box. The upright box has two suction ports at the lower end, midway between which is the water wheel, from each blade of which is a free,

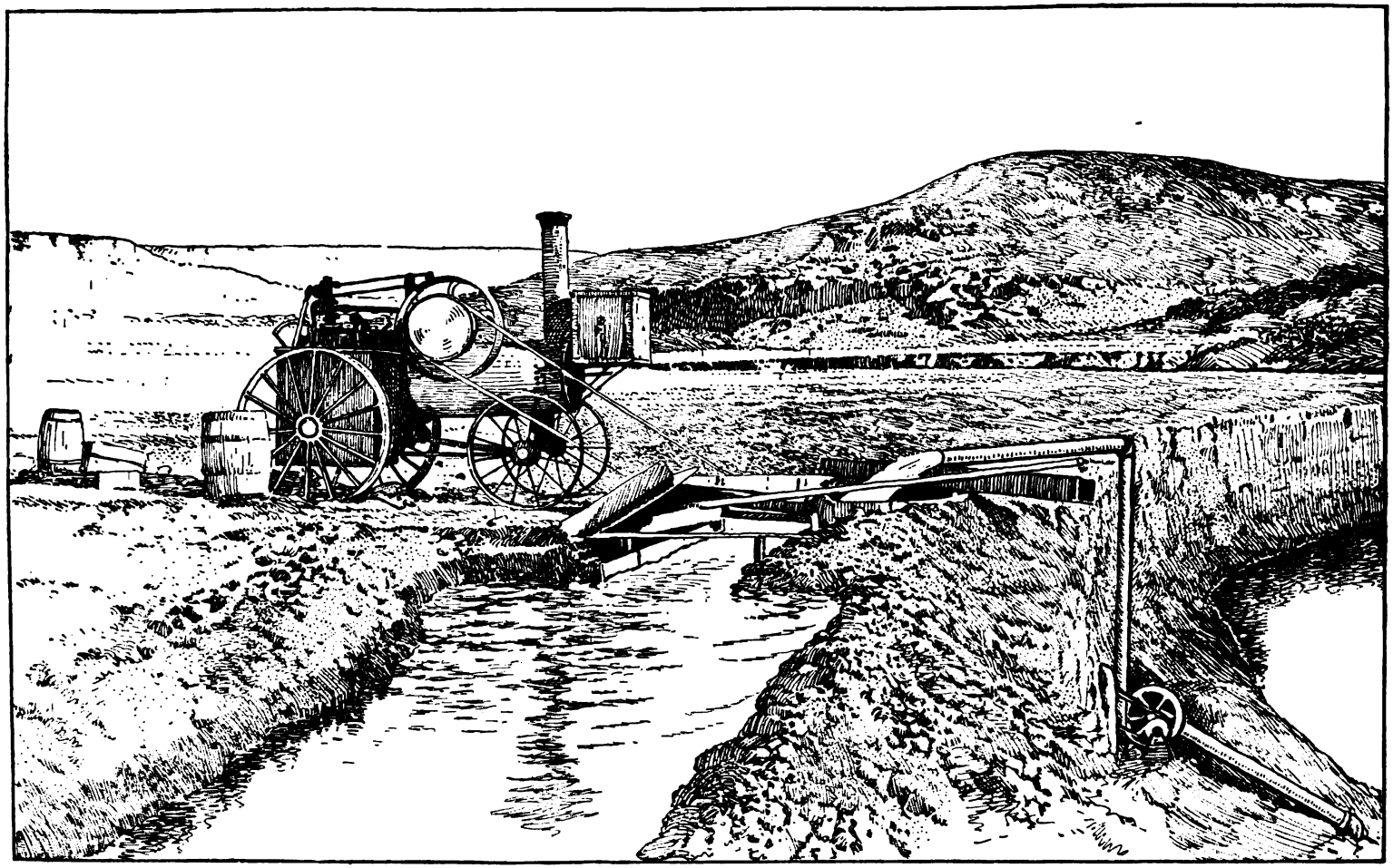
continuous delivery of water, which rises in the vertical box to the discharge outlet. These wheels are made in various sizes, from those which are but 4 by 8 inches up to wheels as great as 16 by 42 inches. The largest of these is claimed to be capable of lifting about 70 second-feet of water, equivalent to about 140 acre-feet per day, to a height of 10 feet on an expenditure of about 100 horsepower. The price of the Menge pump is exceedingly low, about $1,000 for the largest size, equivalent to a first charge for plant alone of approximately $14 per second-foot, plus the usual cost for steam boilers capable of producing this number of horsepower.

CENTRIFUGAL AND ROTARY PUMPS.

For lifting large volumes of water to moderate heights the centrifugal pump (fig. 13, p. 40) is most economical and efficient, as well as simplest in construction and cheapest in first cost of plant and erection. It is not, however, so substantial as a direct-acting steam pumping engine, and therefore not so suitable for large permanent works requiring considerable lifts. Where circumstances are suited to its employment it is one of the best pumps for irrigation. It is adapted to raising water heavily charged with sediment. In construction a centrifugal pump is similar to an outward-flow turbine driven in the reverse direction. Such a pump can not be put in action until it is filled with water, an operation which is effected through an opening in its outer casing when the pump is below water, or by means of a steam jet when the pump is above water. The efficiency of a centrifugal pump diminishes with the lift, and for lifts exceeding 25 to 30 feet a force or plunger pump produces better results. Centrifugal pumps are usually driven by water, steam, or gasoline motors, with which they are connected by belting or shaft and gearing, and they may be erected independently of the motors and at some distance from them (Pl. VIII). They are also made to gear directly on the motor shaft.

Many forms of centrifugal pumps are now in the market. They are of varying capacities, from those having 2-inch discharge pipes up to those having 24-inch discharge pipes, the largest sizes being capable of elevating as much as 15 second-feet, or the same number of acre-feet in a day of twelve hours. Such pumps as these vary in cost according to circumstances, but the larger sizes cost for plant about $100 per second-foot of capacity for moderate lifts, while for 15 second-foot pumps they require engines capable of developing about 5 horsepower per foot of lift.

Among the more notable centrifugal pumping plants for irrigation is one for the Vermilion Canal Company in Louisiana, consisting of six 15-inch pumps, which are claimed to be capable of discharging 130 second-feet of water against a head of 20 feet, and are operated by two engines, each of 250 horsepower. Another centrifugal pump, working on a farm in southern Arizona and operated by a 10-horsepower engine



CENTRIFUGAL PUMP DRIVEN BY THRESHING ENGINE

and boiler, has a capacity of two-thirds of a second-foot. The operation of this plant calls for the consumption of about 1 cord of wood per day of twenty-four hours, and it is capable of irrigating about 3 acres in a season. A similar pump in the same locality and operated by a gasoline engine of 35 horsepower will handle about 11½ acre-feet in twenty-four hours on a consumption of about 84 gallons of gasoline. Other centrifugal pumps of small capacities and capable of watering 5 to 10 acres per day, and in the course of an irrigation season from 50 to 100 acres, are operated by one man at a cost of about $2.50 per acre irrigated for maintenance and $15 per acre for first cost of plant.

It is proposed to erect an extensive centrifugal pumping plant for the Summit Lake Water Company in California, and the estimates of the engineers for a plant capable of irrigating 40,000 acres, including distributing canals and other items, is $81,000, the cost of the pumping plant alone being estimated at about 75 cents per acre, while the cost for operation of and interest on the pumping plant during an irrigating season is estimated to be about $1 per acre, on the assumption that the depth of irrigation will be 1 foot and the lift 20 feet. These figures are considerably below those of most gravity systems.

Rotary pumps, while theoretically the most efficient, are practically capable of elevating but small quantities of water, and have been found of small value in elevating water for irrigation. They may be termed revolving-piston pumps in distinction from direct-action pumps, and have the advantage of not changing the direction of flow of water during its elevation by each stroke of the pump. They can be run at high speed, and have no complicated leather valves or pistons to be choked or otherwise get out of order. They are probably most useful in lifting silt-laden water or heavy fluids. There are numerous forms of these pumps in the market. A large machine of this type, made by the National Pump Company, is stated to be capable of lifting about 5 acre-feet of water in twenty-four hours to a height of 20 feet on an expenditure of about 5 horsepower, and to a height of 100 feet on an expenditure of 25 horsepower. The first cost of this machine is $400, or about $150 per second-foot. The efficiency of rotary pumps is low, there being an excess in driving power required over effective work performed.

MECHANICAL AND SIPHON ELEVATORS.

There are several varieties of mechanical water elevators, nearly all of which act on the principle of an endless chain carrying buckets. This endless chain revolves on two wheels, one at the upper end of the lift and one beneath the surface of the supplying well or stream. As the chain revolves, the buckets dip into the water and become filled, and as they reach the upper end of their revolution they spill their contents into a trough which leads it to the irrigating ditches. Two of the more popular patented varieties of mechanical water elevators are

the link-belt box water elevator and the Seaman irrigating pump. The link-belt box elevator consists of an elongated box which is set up in an inclined position over the water supply, at either end of which is a wheel of peculiar construction carrying on its periphery a metal link belt or chain, attached to which at short intervals are wooden projections of such dimensions as to fill the cross-section of the box. As the chain travels forward these projections are raised, carrying with them the water resting upon them until it reaches the upper end of the box, where it is discharged into the irrigating ditch. This machine may be operated by animal, steam, or water power, and the largest sizes are capable of lifting about 5 second-feet with an expenditure of 7 horsepower for a 10-foot lift. The highest practicable lift of these machines is 20 feet, and one of this capacity costs $50 per second-foot.

The Seaman irrigating pump is similar to the apparatus just described, excepting that instead of a series of wooden flights or projections lifting water in a closed box it consists of a number of large galvanized iron buckets carried by the chain working in the open, the buckets being closed on all sides, with the exception of an opening on the bottom containing a ball valve retained by a little wire basket. When the bucket is filled the ball is pressed down in the basket so as to close the opening, and as the bucket reaches the upper part of its revolution the ball drops in the basket, permitting the water to flow out freely. The largest of these contrivances are capable of lifting about 1½ second-feet on an expenditure of 5 horsepower, the first cost being about $250.

There is manufactured in France, by Lemichel et Cie, an apparatus called a siphon elevator, which is claimed to attain an efficiency of 90 per cent. It consists of a siphon erected at a fall or dam in a river, at a reservoir dam, or in any situation where the lower discharge arm can be carried below the suction pipe so as to give a difference of elevation for the creation of siphon action. At the highest point of the siphon are constructed air and valve chambers, the effect of which is to relieve the siphon at that point of part of the water passing through it, only a portion passing on down through the longer arm of the siphon to keep up siphon action. It is this contrivance which enables water to be elevated by the siphon to heights as great as nearly 30 feet at sea level, instead of being delivered, as by common siphons, below the point from which it is derived.

The siphon elevator (fig. 17) depends for its efficiency on the operation of the air chamber or receiver and the regulator, which are placed at the upper bend of the siphon pipe. At the bottom of the suction pipe is a check valve which allows the ingress of water but prevents its escape. At the bottom of the lower arm of the siphon is a stopcock which, when open, permits the escape of water, so that when it moves a vacuum is created behind it, which is filled with water, as in simple siphons. In action the siphon elevator must first be filled with

water, and as this descends in the lower pipe and ascends in the upper or suction pipe it passes through the receiver (*a*), where it reaches an open check valve which intermittently cuts off its flow into the regulator (*b*). The water forces this valve (*c*) forward until shut, and, its exit being thus cut off, its momentum raises a puppet valve (*d*) in the receiver held down by a spiral spring. Through this valve the water escapes into a storage tank or irrigating ditch. While the regulator is being partially emptied into the pipe a vacuum is caused, which creates a depression in the corrugated heads of the regulator, as in an aneroid barometer, and the pressure on the clack valve (*c*) being diminished, it is thrown open by a weight on a lever, permitting the water to fill the regulator once more and the corrugated heads to again assume their normal position. This vibratory motion occupies but a brief time, as many as 150 to 400 such pulsations taking place per minute, so that the flow of water is nearly continuous.

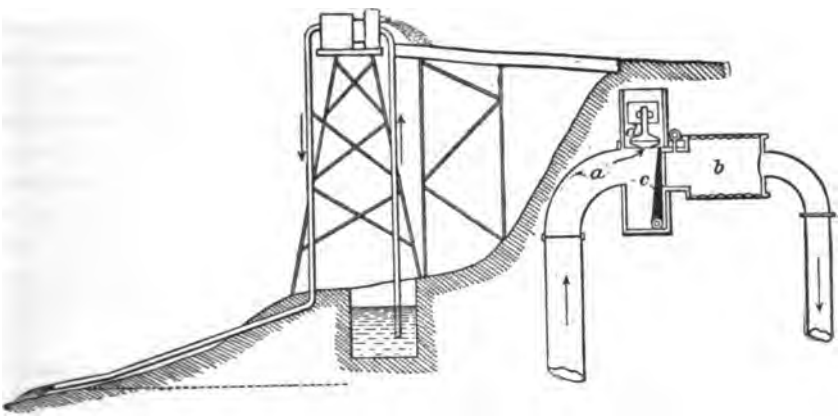


FIG. 17.—General view and detail of siphon elevator.

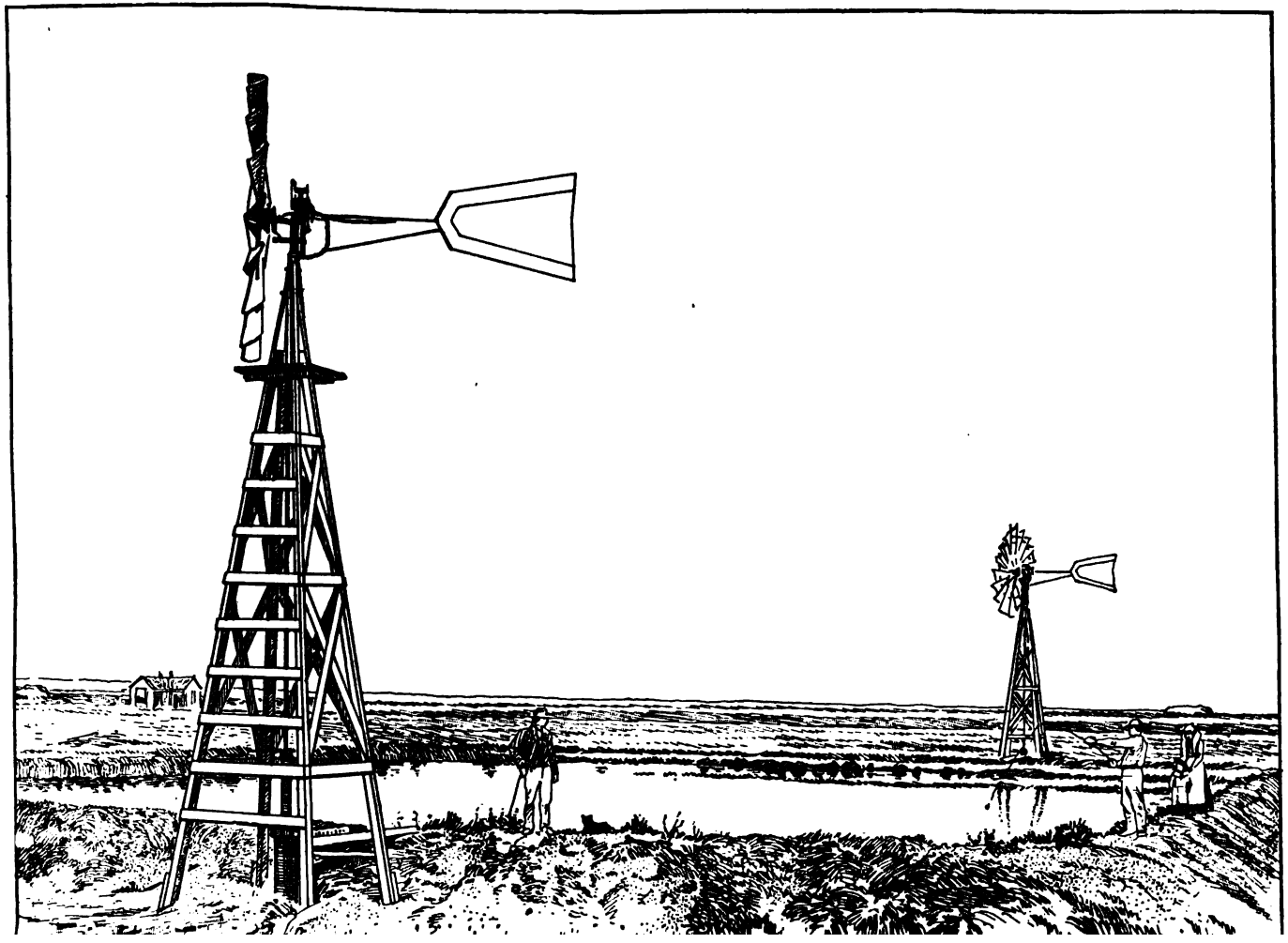
The capacity of these siphon elevators varies according to their dimensions and the height to which they elevate the water, but at sea level they have been built with capacities sufficiently great to elevate 8 acre-feet in twenty-four hours. This is a very large quantity when the simplicity of construction and cheapness of first cost of this mechanism—about $1,200—are considered; and it may be safely stated that if further experiment with it shows it to be as effective as claimed in the past, it will be a valuable water-lifting apparatus where only trifling heights—say 10 to 15 feet—are to be overcome and there is sufficient fall and surplus water to permit of the wastage caused by the operation of the siphon. Batteries of two or three of these siphon elevators have been erected, one above the other, whereby, with additional wastage of water for each siphon, heights two or three times those to be effected by one siphon elevator have been obtained.

STORAGE RESERVOIRS.

The storage reservoir or tank employed to retain water which has been pumped when not required for irrigation should be situated at the highest point on the irrigable land. When there is but little slope to the land it may be impracticable to build an earth reservoir at a sufficient elevation to obtain a good head, in which case a wooden or metal tank should be used. Such tanks can be gotten from any of the windmill makers, and range from 10 to 30 feet in diameter, their depths varying between 3 and 20 feet and their capacities from 1,000 gallons upward. These tanks (Pl. II, p. 30), when constructed of wood, are made of the best selected clear pine and are bound by from 3 to 20 iron hoops, depending on the dimensions of the tank. Their prices range from $30 to $800 each.

Where artificial reservoirs can be constructed on the land, it is best, provided suitable material for rendering them impervious can be found, to build them up by constructing about the reservoir an embankment rather than by making an excavation in the ground. The reason for this is that the former mode of construction places the water surface at some height above the ground level and, besides making a larger volume of the water supply available, gives a better head for flowing it through the ditches. The most economical way in which to construct such reservoirs is to find a gully or depression of some sort in one of the higher portions of the land and build across the lower end of this an earth embankment. This is rarely possible on the level plains, where it is necessary to wholly surround the basin by an artificial embankment.

For the latter type of reservoir the best shape is circular, as such is more easily built and has a larger capacity for the same amount of material moved (Pl. IV, p. 34). The ground should first be deeply plowed and stripped of the surface soil, and this loose material be used as a portion of the outer face of the inclosing embankment. The cross-section of the latter should be rather flat, its slopes depending upon the nature of the soil. Where a firm, clayey gravel can be obtained, free of vegetable mold and other foreign substances, this will make one of the most impervious embankments. It may be given a cross-section as steep as about 1½ horizontal to 1 vertical on the inside, and about 2 horizontal to 1 vertical on the outside, with a top width of not less than 4 feet. For less suitable material, as more sandy soil, or that containing some admixture of loam, flatter slopes must be used, reaching even as low as 3 horizontal to 1 vertical inside, and 3½ or 4 to 1 on the outside. In every case such an embankment should be built up in horizontal layers, well and deeply bonded with the subsurface soil, these layers not exceeding 6 inches in thickness and being separately tramped by animals or rolled by heavy rollers as laid. If there is available a gravel containing sand and a little clay matter, the embank-



ment may be built up dry, and will form one of the most impervious structures that can be made. With less firm materials a puddle wall should be built up through the center of the bank as it is erected. Such a puddle wall should consist of gravelly clay, moistened as it is laid, and at least 2 feet in thickness for low embankments, its base being firmly and deeply bonded with the subsoil. The top of the embankment should reach at least 2 feet above high-water surface (Pl. IX), in order to prevent its being overtopped by waves during high winds, and the outer slopes should be sodded to protect them against erosion by heavy rainfalls. The reservoir should not be too large for the pump to easily fill, in which case the percentage of loss from evaporation and absorption would be too great. It should be as deep as practicable, for the deeper the less its area and the less the surface exposed to evaporation and absorption. A reservoir 100 feet in diameter and 5 feet deep will lose nearly all its water in a few months, whereas one 50 feet in diameter and 10 feet deep will lose scarcely 25 per cent by absorption and evaporation in the same time.

If homogeneous clayey soil underlies the bottom of the reservoir it will be unnecessary to provide a lining, though there may be some loss of water through percolation and absorption. If such a surface is not available for the bottom, the soil should be removed and the subsoil covered with a layer at least 1 to 2 feet in thickness of clay and gravel, the same being carefully puddled and rolled over the entire surface and up the inner slope of the embankment so as to make a firm bond with it. Better still, if means permit, is it to line the inner surface of the reservoir bottom and slopes with asphaltum. This is put upon the denuded subsoil much as is the asphaltum used in paving city streets. One of the best admixtures is about 75 per cent of La Petra asphalt, the remainder being of Las Conchas as a flux, both of which come from Lower California. This is boiled in open kettles for twelve hours at a high temperature, frequently stirred, and 20 per cent of it by weight is mixed with 80 per cent of sand previously heated to the same temperature. This should be put on with a thickness, for shallow reservoirs, of 2½ inches, spread with hot rakes, tamped with hot tampers, and held in place on the slopes by anchor spikes of sheet iron about an inch wide and driven in at intervals of about a foot. This lining should be painted over with a bitumen paint or Trinidad asphaltum fluxed with residuum oil and poured on hot from buckets. Such a lining laid over a well-leveled and well-rolled surface will last many years, will be impervious to water, and as it will cost but 15 to 20 cents per square foot, will probably more than pay for itself in a short time in the saving of water.

To control the flow of water from the storage reservoir a discharge or outlet gate should be firmly built into the banks in such manner that seepage water will not find its way along it and thus erode the reservoir wall. It should be located at the lowest point of the reservoir bed, which may be previously graded to slope toward it. Such

an outlet sluice may be satisfactorily constructed of wood by building out wing walls on both the outer and the inner surfaces of the embankments and inclining its bottom ends downward into the ground so as to prevent the seepage of water about the resulting box-like channel or flume. Additional security against the travel of seepage water may be had by running a row of sheet piling tightly connected with the box flume back through the center of the embankment for some distance. In this box flume should be erected a small lifting gate which can be raised to any desired extent so as to permit of the discharge of such volumes as may be required in irrigating the fields.

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DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

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OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 2

IRRIGATION NEAR PHŒNIX, ARIZONA.—DAVIS

WASHINGTON
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1897

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UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

IRRIGATION NEAR PHŒNIX, ARIZONA

BY

ARTHUR POWELL DAVIS

WASHINGTON
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1897

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, January 25, 1897.

SIR: I have the honor to transmit herewith a paper entitled "Irrigation near Phœnix, Arizona," by Arthur P. Davis, hydrographer, and to recommend that it be published in the series of papers "in relation to the gauging of streams and to the methods of utilizing the water resources," the printing of which was authorized in the act making appropriations for sundry civil expenses of the Government for the fiscal year ending June 30, 1897, approved June 11, 1896.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

PREFACE.

The storage of flood waters on a large scale is fast coming to be a matter of prime importance in connection with the development of the arid portions of the United States. The irrigation projects which involve comparatively small expenditure, or which can readily be handled by associated effort, have already been entered upon, but there still remain many localities where, as time goes on, the necessity for water conservation becomes more and more pressing. This is especially the case in southern Arizona, in the Salt and Gila valleys. Here, under the genial semitropic conditions, large returns are obtained from the fertile soil, some of the most valuable fruits are raised, and crop follows crop in rapid succession, farming operations being continued throughout the year.

The success of agriculture has been such that a considerable number of large irrigating canals have been built and lateral ditches extended until the available supply during low water has been practically exhausted. The streams of this country are, however, extremely irregular in character, fluctuating at times with great rapidity, floods coming down without warning, and disappearing in the course of a few hours. At certain seasons of the year high waters prevail and run to waste to the Gulf, or disappear by evaporation and percolation into the sandy desert. It is obvious that by providing suitable storage works the area of land to be irrigated can be greatly increased, the limiting conditions being practically the cost of storing water relative to the value of the crops produced.

The conditions briefly described above are not peculiar to the vicinity of Phœnix, or even to the Territory of Arizona; they prevail in greater or less degree throughout the more arid parts of the United States, for in nearly every portion of this country irrigation has been demonstrated to be successful and largely profitable. Systems of water supply have been built, the more easily available waters utilized, and the extension of irrigable lands now rests mainly upon the conservation of waste waters. It is for this reason that a discussion of the conditions near Phœnix, Arizona, has an interest not only to the citizens of that locality, but in general is of value to residents in other portions of the West. In certain respects the needs for water are more

pressing in southern Arizona than elsewhere, and thus the probabilities of early solution of some of the problems of water storage are here more likely to be settled in the near future. For this reason the following paper by Mr. Davis will be of benefit to a larger circle of readers than those to whom, from the title, it may appear to be addressed.

In order to make clear all of the surroundings, Mr. Davis gives a general description of the topographic and climatic conditions of the Salt and Gila valleys, and of the irrigation works already constructed. He also mentions the legal complications which have arisen, and outlines some of the projects now being constructed. He points out the great natural advantages of this country, and shows as far as data can be procured the facts relating to water supply, evaporation, silting of reservoirs, and other factors which make or mar projects of water conservation.

At first sight the storage of water appears to be a very simple matter. In popular discussions it is common to assume that the only steps necessary are to place rock or timber obstructions in some of the many canyons or narrow places along the course of the river in order to hold back the water of floods, and later allow it to flow down the stream as necessity requires. On carefully examining any proposition of this kind, many obstacles are found to arise, some of these natural—such as the difficulty of finding a proper location, the expense of laying foundation, and the liability of the reservoir to fill by silt—and others artificial or legal, such as interference with vested rights, and difficulties of securing title to the stored water after it has left the reservoir and is on the way to the land to be covered.

A traveler going over the Territory sees here and there almost numberless places where it appears probable that a storage dam might be built holding behind it considerable water, but when a careful survey has been made it is usually found that the slope of the stream is so great that if a dam were built the amount of water held behind it would be relatively too small to repay the cost of construction. Should it be found that there is ample space behind the selected dam site, further investigation may reveal the fact that solid rock can not be found at moderate depth beneath the surface. In other words, the stream has washed into the gorge such a mass of loose material as to fill it to a depth of 20, 40, or even 60 feet or more. To remove this, place the foundation on bed rock, and then rear a structure to the proper height, will necessitate the expenditure of such large sums as to render the enterprise impracticable. This is a very common condition within the arid region, where the drainage lines, dry for a great part of the year, are filled, perhaps for a few days or even a few hours only, with a great torrent resulting from excessive local rainfall. The water discharged down the steep slopes dislodges not only the accumulated sand and dust which has been blown about by the desert winds, but rolls along gravel and bowlders into the channels. Even

in the narrow gorges through which these sometimes pour the velocity of the water is not sufficient, except perhaps in extraordinary floods, to tear out the loose material and reach bed rock. Thus the gravel and bowlders accumulate during the lesser floods all along the course of the stream, covering the dam sites, and form long lines of barren wash.

Not only does the loose material transported by the floods cover the bottom of many otherwise feasible dam sites, but deposits of this character constantly imperil and shorten the life of all storage reservoirs. The flood waters bear this along, and when brought to rest drop the heavier material at first and then the lighter, retaining only the finest particles, the greater part of which in time may settle within the interstices of the coarser. Thus the upper ends of all reservoirs are rapidly filled with silt, and it becomes an important question to the projectors of storage works as to how many years will elapse before the value of the reservoir is practically destroyed and whether its use can be restored in part by subsequent removal of some of this material.

The legal obstacles are in many localities no less vexatious than those offered by nature. While many principles have been settled in regard to the use of water for irrigation, their application to particular cases is still a matter of doubt. Even in the case of persons diverting water from perennial streams there are innumerable controversies whenever a shortage occurs. But when a portion or all of the surplus water is being held in reservoirs and returned perhaps to the same stream, to be again recovered, there can not fail to be still greater complications than those now brought to the attention of the courts. The primary cause of most of the contentions which arise is the lack of exact knowledge concerning the amounts of water which are flowing in the streams from day to day and the quantities taken out by different canals. These are not only fluctuating, but the matter is complicated by the disappearance of water by evaporation and the reappearance of other waters in the natural drainage lines by seepage from canals above, or from the slow progress of water coming originally from rainfall and finding its way gradually toward the lowest points.

When one has noted the interminable lawsuits over water rights and appreciated the fact that most of these are due to lack of precise knowledge as to past conditions, it appears almost incredible that greater care is not being taken to ascertain exactly how much water is flowing at different points in the natural streams, especially in view of the fact that later large investments are to be made in storage projects. It is, however, a lamentable fact that very little attention is given to this matter, mainly perhaps because the persons investing in irrigation works are usually from humid climates, and it never occurs to them that rivers do not always have water to spare within their

channels. Yet in southern Arizona, where, as in other portions of the arid regions, the rivers at certain seasons of the year diminish and even cease flowing, enormous investments are being made upon crude assumptions as to the quantity of water available, these assumptions being supported only by a few isolated facts or measurements.

The determining point in the construction of storage works, after their feasibility has been settled upon, is whether they will pay—whether the value of the water thus obtained and the benefits derived are sufficient to make the projects remunerative. The answer to this question depends largely upon what may be considered as profitable; for example, if these storage reservoirs are under consideration by corporate enterprise, it will be necessary to show that the annual water sales or rentals will not only repay the expense of management and a fair interest on investment, say 6 or 8 per cent, but will also yield a surplus which can be used as a sinking fund to repair damages or ultimately cover the cost of the works, should these be gradually deteriorated by accumulation of silt. The aggregate of these items is large and may amount to 10 per cent or upward. Thus it is necessary to show that the storage works will, after completion, pay for themselves within a brief period; otherwise individual capital will not be attracted.

If, on the other hand, these reservoirs, or the best of them, are built by the whole community interested or by State or national funds, the question of immediate profit does not enter so largely into the calculations. In this latter case the indirect benefits to be derived by the people offset to a certain extent the interest charge, and if the works can be shown to pay the cost of maintenance and provide a small sinking fund, they may be considered as feasible. Thus it is that a project which will be condemned by the investor as worthless may at the same time be of the utmost value to the community and one which would well repay cost of construction if this cost were distributed uniformly to all benefited.

The situation in the Salt and Gila river valleys is fairly typical of that elsewhere as regards the probable profits to be obtained by constructing storage reservoirs. Briefly stated, it may be said that the canal systems already constructed or partially completed cover a larger area of land than can be supplied by the average summer flow of the streams. Water from reservoirs is needed for lands already under ditch and whose owners have already purchased water rights. There are above these ditches still larger tracts of land which would be valuable if water could be had, but it is apparent that the greatest good would result from securing an ample supply of water to the lands already partly cultivated rather than indefinitely increasing the area of poorly watered farms.

If a corporation contemplates building a reservoir within the Gila Basin, the first question is, Shall the attempt be made to sell the water

to lands already under ditch, or shall this water be taken to areas now desert? The former plan would be perhaps the best for all concerned; but experience has shown that there is no certainty that the owners of lands now partly supplied with water will purchase additional water rights, even though these would assure an ample supply at all times. This is due partly to the fact that many of these lands now under ditch are held by speculators, hoping for a general rise in land values—such a rise as will follow the construction of storage works. In other cases the lands are held by farmers, who, although cultivating a considerable part of their land, hesitate about purchasing additional water rights, preferring to try to get along with a deficient supply rather than risk additional outlay. Thus it has happened that similar enterprises of this character, where the water was apparently in great need, have been forced into bankruptcy by the accumulation of interest and maintenance charges during the period following construction and before the water rights could be sold to bona fide irrigators.

By the construction of storage works commanding the valley lands, there necessarily results an increase in value of every acre even though water rights have not been purchased, from the fact that there is a possibility of purchasing these. Upon the completion of such works, there takes place what is termed an unearned increment of value of all lands, for with the assurance of a larger supply even to other portions of the valley the chances of securing water in one way or another are increased. This increment of value is in round numbers equivalent to the cost of the storage works, and if it could be transferred from the pockets of the recipients, who have done nothing to deserve it, to the hands of the persons who have built the works, accounts would be balanced and it would be possible to construct these great enterprises. As a matter of fact, however, the association or group of men who build a reservoir must look to voluntary purchases by individuals slowly purchasing water rights for lands already owned or must seek reimbursement by putting the water upon desert lands and selling land and water.

This latter method, that of a storage company selling land and water together, is apparently the only feasible mode of procedure. It necessitates, however, not only the acquisition of reservoir site and expensive construction of storage works, but also, as a rule, the building of canal lines and the acquisition of large bodies of desert land, the latter being a contingency for which the land laws of the United States make no provision. If by one means or another such lands can be secured, directly or indirectly, the question of profit rests mainly upon the ability to dispose of these lands at a rate sufficiently rapid to prevent the accumulation of such indebtedness as often sweeps away a newly completed project. The tendency is, therefore, to extend irrigation by stored waters to new areas where land can be obtained at a nominal price and sold at a sufficient advance to repay

the cost of construction, rather than attempt to supply water to lands already under ditch and partly irrigated.

Some of the best storage projects, however, are so situated that the water can not be taken readily to new areas, and it appears probable that these, although among the most important in the country, can only be constructed by the adoption of some scheme by which all of the lands of the valley benefited directly or indirectly will be forced to contribute an amount equal to the benefits derived. This is possible only under some system similar to that of the district organization in California, where all of the lands receiving water from a given source are assessed. Here it is not necessary to consider whether the enterprise will be money making in itself. Thus it is possible to push forward the construction of beneficial works which otherwise never could be built.

F. H. N.

THREE-YEAR-OLD ALMOND GROVE NEAR PHŒNIX, ARIZONA.

IRRIGATION NEAR PHŒNIX, ARIZONA.

By Arthur P. Davis.

TOPOGRAPHIC FEATURES OF ARIZONA.

The Territory of Arizona covers approximately 113,000 square miles, of which about 39,000 lie below the altitude of 3,000 feet, about 27,000 lie between the contours of 3,000 and 5,000 feet, and about 47,000 lie above the elevation of 5,000 feet. The highest point in the Territory is San Francisco Mountain, in the northern part, which reaches an altitude of nearly 13,000 feet. The Territory is sharply divided into two characteristic portions by the trend across it of the main axis of the great Colorado Plateau, from the northwestern corner of the Territory in a nearly southeasterly direction. This plateau slopes gently to the northward, but on the southwestern side breaks off suddenly throughout most of its course, and its steep slope is deeply carved by lines of erosion. Almost the whole of that portion of the Territory which is below an elevation of 3,000 feet lies to the southward of this escarpment.

To the north of the escarpment the temperature ranges from that of the temperate zone to that where snow is nearly perpetual, on the summits of the San Francisco and White mountains. The southern portion of the Territory is characterized by temperatures which may be designated as ranging from temperate, along the foothills of the Colorado Plateau, to semitropic, in the lower valley of the Gila and Colorado. The southern portion of the Territory may be again subdivided into two portions, that draining directly into the Colorado and lying to the westward of Prescott, and the greater portion to the south and east, which forms the great Gila river system. The Colorado Plateau is partly of igneous origin, and a great portion of it is somewhat pervious to water. Its northern slope for a considerable distance from the summit is very gentle, and though the precipitation is greater than in most portions of the Territory, it is very meagerly marked by

drainage lines and almost destitute of water. Sharply contrasted with these facts are the conditions on the southern slope. Here, through most of its course, the plateau drops off with a very steep slope, which is deeply cut with drainage lines in which are living creeks and rivulets of clear, beautiful water, such as San Francisco River, Black Creek, Bonito Creek, White River, Carrizo Creek, Cibicu Creek, Box Creek, Cherry Creek, Tonto Creek, Wild Rye Creek, East Verde River, Pine Creek, Fossil Creek, Clear Creek, Beaver Creek, etc.

The region of high altitude, as before remarked, lies largely north of the divide, while the great bulk of the water flowing from the plateau, as proved both by erosion of drainage lines and by the volume of permanent streams, flows away to the south. The explanation of this is partly the porosity of the strata composing the plateau, which allows the water to sink instead of flowing off the surface. Once underground, its egress to the south is favored by the shorter distance which it must percolate on a given grade before reaching a surface, due to the more abrupt slope.

Another partial explanation is found in the meteorological condition. The moisture of this region is brought from the Pacific Ocean and the Gulf of California by the prevailing southwest wind. As this wind ascends the elevations toward the Colorado Plateau, its temperature is lowered, which reduces its capacity for holding moisture and increases its relative humidity. When this quantity reaches 100 per cent in any part, precipitation occurs. This influence continues until the wind passes the summit, where the process is reversed.

As might be expected, therefore, the hydrographic resources of the country immediately southwest of the Colorado Plateau are disproportionately great when compared with those to the northward. For instance, the precipitation at Fort Apache, as shown by a mean of twenty years' observations, is 19.75 inches, the elevation being 5,050 feet, while the precipitation at Holbrook, at an elevation of 5,047 feet, on the northern slope, is 8.47 inches, as indicated by the mean of ten years' observations. This is an important fact, especially when taken in connection with the fact that the great areas of valley land with a semitropic climate lie in the southwestern portion of the Territory, and are easily covered by the streams which are formed by the conditions above described, and which constitute the main features of the great Gila river system.

GILA BASIN.

The drainage area of Gila River, including a number of small lost basins which are topographically tributary but which seldom or never furnish any run-off to the main stream, is about 72,000 square miles, of which nearly 57,000 lie in the Territory of Arizona, about 14,000 in New Mexico, and something over 1,000 in Mexico. The areas in

the United States are distributed, with respect to elevation, approximately as follows:

Distribution of area of Gila Basin by altitude.

Elevation.	Per cent of area of basin.	Area, square miles.
Under 1,000 feet	9	6,400
Between 1,000 and 2,000 feet	19	13,500
Between 2,000 and 3,000 feet	16	11,400
Between 3,000 and 4,000 feet	14	10,000
Between 4,000 and 5,000 feet	15	10,700
Between 5,000 and 6,000 feet	12	8,500
Between 6,000 and 7,000 feet	8	5,600
Over 7,000 feet	7	4,900
Total	100	71,000

Gila Basin is conveniently divided into four parts. Of these, the most northerly is Salt River Basin, which includes all the territory tributary to Salt River. This again is sharply divided into its valley and mountain portions. Salt River Valley (see map, Pl. XXX) may be taken as including all the territory adjacent to Salt River from its mouth up to the junction of the Rio Verde. Above that point the greater portion of the basin is mountainous, with small valleys on the Rio Verde, in Tonto Basin, and at a few points on Salt River and other tributaries. The Lower Gila district may be taken as the portion lying below the mouth of Salt River; the Middle Gila district, that portion from the mouth of Salt River to The Buttes above Florence and including the Pima Indian Reservation and the great Casa Grande Valley. The Upper Gila district includes the valley in the region of Camp Thomas and Solomonsville and the tributary mountainous districts. In addition to these main divisions of the trunk streams may be taken the subordinate divisions of tributaries, such as San Pedro, Santa Cruz, Hassayampa, and Agua Fria creeks.

TEMPERATURE.

The tables of temperature for the Gila and Salt River valleys show that the climate is very warm. But care should be taken not to exaggerate this feature, for the actual conditions in their relation to human life and comfort are by no means as unfavorable as they might appear to persons comparing these tables of temperature with those of some Eastern localities. For about eight months in the year the temperature of this valley is delightful. Cool nights, bracing mornings, and

bright, pleasant days are the rule, except in the months of June, July, August, and September. In these months the heat becomes intense, and though there is of course some variation, the temperature remains continually high throughout the greater part of this period.

The physiological effect of this heat is markedly modified by the aridity of the climate. The human economy provides that when the temperature of the healthy body rises above the normal the perspiratory glands begin to act and furnish the skin with moisture, the evaporation of which lowers the temperature of the body. An essential condition of this natural safeguard against excessive heat depends upon the ready evaporation of the moisture furnished by nature. In a very humid climate this evaporation can not occur; and in those portions of the country where the humidity is comparatively high such evaporation must be proportionately tardy and sluggish, so that any considerable temperature above normal blood heat produces great suffering and exhaustion, and even prostration. In an arid region, on the contrary, the low percentage of humidity causes prompt and quick evaporation of the moisture and the consequent success of nature in its attempt to prevent uncomfortable and injurious bodily temperature. In southern Arizona these favorable conditions for resistance to heat are at their maximum. Though the temperature is high, the relative humidity is very low, and every particle of moisture which reaches the surface of the skin is promptly evaporated—so promptly that its presence is not perceived—and while the body is thus kept at its normal temperature the unpleasant effects of excessive moisture are not experienced, and the sultry, sticky days so common in the East are unknown in Arizona.

The principles involved in these facts are frequently illustrated to the sojourner in southern Arizona in the following manner: Riding in a wagon or buggy in the month of July the traveler may feel greatly oppressed and enervated by the intense heat; the climate seems well-nigh insupportable; but if he will get out and walk for a short time, the circulation induced by the exercise starts the perspiration and the traveler is surprised to find himself greatly refreshed, and he may then resume his ride in comfort. Farm labor, the construction of canals, the rounding up and branding of cattle, and other active, hard labor are performed at any time in the summer with less comfort, of course, but with no worse effects, than at any other time of year, and without actual suffering, the only requisite being plenty of drinking water.

A fair comparison of the sensible temperatures of two places may be obtained by a comparison of the readings of wet-bulb thermometers. The difference between the readings of wet and dry bulb thermometers here often exceeds 30 degrees. The summer is, therefore, far from being as uncomfortable as might be supposed, and the delightful autumn, winter, and spring fully compensate for the discomforts

of the summer months; and the climate, taken as a whole, with its extreme aridity, its mildness, and its large proportion of sunshine, is exceptionally healthy and especially beneficial to those suffering from bronchial or pulmonary troubles.

RAINFALL.

Rainfall records of Arizona, from the date when they began up to and including the summer of 1890, were prepared by Capt. William A. Glassford and published in a Report on the Climatology of the United States, with Reference to Irrigation, by Gen. A. W. Greely, Chief Signal Officer.[1] Later records may be found in the various annual and monthly publications of the Weather Bureau, and it is deemed of value to reproduce some of them here, brought up to date, partly because of the scattered condition of the original records, some of them being now out of print, and partly for the reason that for purposes of irrigation the season is best divided about the end of August. Rainfall occurring after September 1 can not in most cases be relied upon for irrigation use in that season, but may be stored for use in the following year. Precipitation occurring before this date may usually be utilized the same year, especially if storage is provided.

No arbitrary line can be drawn separating the precipitation available in one year from that available only by storage for the next, but it is thought that more cases will occur where September precipitation can be used the same year than where August precipitation can not, and that it is fair to divide the season as above indicated. For the convenience of those contemplating storage works, therefore, the tables are rearranged and the total annual rainfalls recomputed on this basis. A glance at the annual and monthly means shows at once that agriculture in the valleys of southern Arizona must depend entirely upon irrigation.

Short fragmentary records in Arizona are of very little value, on account of the erratic nature of Arizona rainfall, which is peculiarly marked during the summer rainy season. This season is characterized by sudden violent local thundershowers, often called cloudbursts, and while in a long series of years such local storms probably distribute themselves with a fair degree of uniformity over districts governed by the same general conditions, yet a short record may be so affected by them as to be abnormal. A station receiving one or more storms of this character, or being avoided altogether, as is likely to occur in a short record, may give results that will be very misleading. For instance, at Fort Lowell, which is but 9 miles east of Tucson, and only 4 feet lower, there fell during July and August, 1878, 0.60 and 7.88 inches of rain, respectively, while at Tucson during the same months the rainfall was 5.72 and 4.71 inches. Such discrepancies would probably disappear

[1] Fifty-first Congress, 2d session, H. R. Ex. Doc. No. 287, Irrigation and Water Storage in the Arid Regions.

in the average of a long series of observations. Very short records, on account of the great secular variations even in countries of greatest uniformity, can not be depended upon as giving the average rainfall for the region in which they are taken. In this climate, for the reasons given above, they are of little, if any, value, even when a long record exists in such situation that a comparison of its mean with that of the short record may be made.

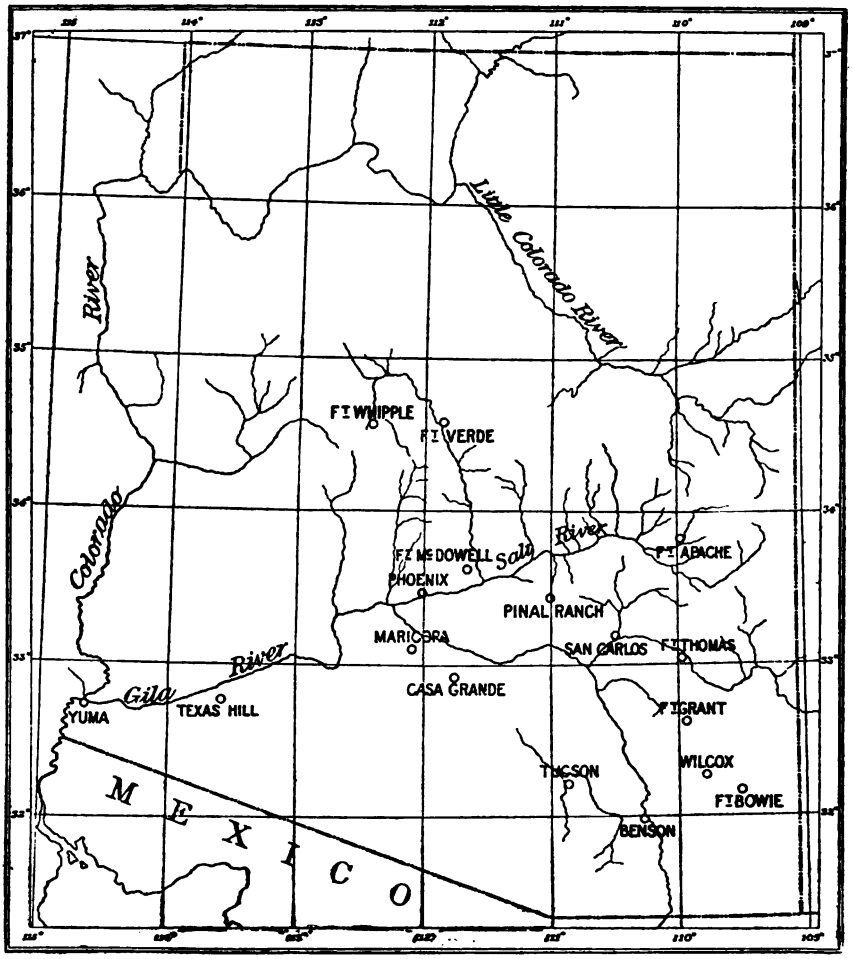


FIG. 1.—Map of Arizona, showing location of rainfall stations.

In a region like Arizona, where the water supply bears such a vital relation to its prosperity, and where, moreover, the means available for keeping rainfall records are limited, rainfall stations should be, and usually are, so far as practicable, widely distributed over the Territory, in order that all varieties of elevation, topography, latitude, and climatic conditions may be represented. Such records, if care-

fully kept for a long series of years, say twenty or more, become valuable for determining the actual rainfall to be expected in any particular locality by means of a short record embracing four or five years. The comparison of such short record with the synchronous record at the station of long observation establishes an approximate relation between the point under investigation and the point at which the long record was taken. In a similar manner a comparison may be made between the measured discharge of any given stream and the synchronous rainfall at the old station, and in a few years a relation can be thus established from which may be derived an approximate hypothetical history of the stream or hydrographic basin under investigation.

The value of these old records, which, unfortunately, are very rare, depends chiefly upon their continuation. It may be broadly stated that the older such a record becomes the stronger is the argument for continuing it. It is especially to be deplored, therefore, that some of the old records in Arizona have been discontinued. For instance, Fort McDowell, having in 1891 the oldest continuous record in Arizona, was in that year discontinued, and has not since been resumed. A great part of the value of this old record might be restored if it were practicable to reestablish the station.

A selection has been made of 16 stations, most of them having a record covering at least fifteen years, so distributed as fairly to indicate the means and extremes of precipitation in the various portions of the basin. A short record at Pinal ranch, not hitherto published, is also included. These records are contained in the following tables:

Record of precipitation at Fort Whipple, Yavapai County.

[Latitude 34° 33′, longitude 112° 28′; elevation, 5,389 feet. Authority, United States Hospital Service and Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1866-67...	3.65	0.57	0.08	0.31	1.72	1.16	8.00	0.06	1.17	0.00	2.70	2.38	21.80
1867-68...	.....	0.10	0.20	2.20	2.97	5.30	0.50	1.00	.....	0.00	6.16	2.72	.....
1868-69...	0.30	0.55	1.50	4.40	0.80	0.92	.....	.....	.....	.....	.....	.....	.....
1869-70...	[1.08]	1.40	1.45	0.00	0.00	1.20	1.09	0.26	1.73	0.24	7.98	3.49	19.92
1870-71...	0.00	1.59	0.30	0.53	0.70	1.01	0.10	1.92	0.47	0.00	4.00	1.80	12.42
1871-72...	1.51	1.40	0.52	0.00	0 50	0.80	0.12	1.62	1.47	1.24	3.74	6.25	19.17
1872-73...	0.04	0.24	0.00	0.64	0.00	1.00	0.23	0.17	0.40	0.42	1.56	4.78	9.48
1873-74...	0.30	0.00	0.80	2.55	5.51	5.68	3.56	1.70	0.65	0.00	5.72	1.56	28.03
1874-75...	0.00	0.50	.....	.....	.....	.....	.....	.....	0.00	0.00	5.92	1.66	.....
1875-76...	0.77	0.00	0.18	0.63	4.60	0.01	0.83	0.51	0.52	0.25	3.23	4.51	16.09
1876-77...	0.72	0.93	0.00	0.00	0.36	0.56	0.49	1.50	1.82	0.00	1.29	0.24	7.91
1877-78...	2.42	1.36	0.00	2.23	0.28	2.02	0.48	2.86	0.33	0.33	0.91	6.34	19.56
1878-79...	0.61	0.00	0.45	1.02	0.91	0.94	0.05	0.03	0.00	0.05	1.87	2.20	8.13
1879-80...	0.68	0.37	1.58	4.21	0.35	0.16	0.11	0.52	0.00	0.04	2.34	2.80	13.16
1880-81...	1.26	0.18	0.42	1.84	0.16	0.10	2.91	0.67	0.42	T.	3.27	5.25	16.48
1881-82...	1.69	0.33	0.30	0.33	2.53	2.04	0.00	0.28	0.45	0.47	1.64	3.34	13.40
1882-83...	2.57	0.39	1.55	0.00	0.31	0.63	2.33	0.86	0.15	0.09	3.20	3.26	15.34
1883-84...	0.33	0.43	T.	4.54	0.25	6.55	5.51	1.62	1.45	0.32	1.33	1.57	23.90

Record of precipitation at Fort Whipple, Yavapai County—Continued.

[Latitude 34° 33′, longitude 112° 28′; elevation, 5,389 feet. Authority, United States Hospital Service and Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1884-85...	0.99	1.42	0.16	5.58	0.08	0.46	1.47	0.62	0.37	0.07	2.53	1.24	14.90
1885-86...	0.11	0.38	2.46	0.32	5.99	1.15	3.04	1.18	0.03	0.00	0.61	4.41	19.68
1886-87...	0.46	0.23	1.68	T.	T.	3.12	T.	2.57	0.43	0.57	2.64	0.71	12.41
1887-88...	4.88	0.05	1.57	0.82	1.30	1.68	1.66	0.52	1.96	0.00	2.49	1.42	18.35
1888-89...	0.62	1.75	3.18	2.94	1.73	1.35	2.91	0.19	T.	0.02	1.45	1.51	17.65
1889-90...	2.11	1.76	0.42	7.38	2.29	3.02	1.52	0.86	0.00	0.06	2.19	2.67	24.28
1890-91...	1.48	.....	.....	.....	0.00	5.96	0.86	T.	0.27	0.00	1.86	3.04	.....
1891-92...	1.48	0.00	0.00	1.19	1.98	1.64	1.91	0.58	0.85	0.00	1.74	2.04	13.41
1892-93...	0.14	1.41	0.00	0.61	1.18	0.47	3.26	0.00	0.88	0.00	1.31	4.30	13.56
1893-94...	0.57	0.15	1.16	0.73	0.30	0.30	0.88	0.00	0.23	T.	1.13	3.88	9.33
1894-95...	0.45	1.37	0.00	3.43	4.37	0.55	T.	0.25	0.50	0.00	0.88	3.53	15.33
1895-96...	0.09	0.24	3.59	0.50	0.55	0.20	0.81	0.35	T.	0.14	4.70	2.61	13.78
Mean..	1.08	0.66	0.84	1.75	1.44	1.10	1.59	0.81	0.59	0.15	2.77	2.95	16.06

Record of precipitation at Fort Verde, Yavapai County.

[Latitude 34° 32′, longitude 111° 47′; elevation, 3,160 feet. Authority, Signal Service and United States Hospital Service.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1868-69...	.....	.....	.....	0.27	0.34	1.72	1.00	0.09	0.08	0.83	0.07	7.26	.....
1869-70...	0.00	0.02	4.04	0.00	0.50	0.01	0.50	0.15	0.00	0.22	3.06	0.89	9.39
1870-71...	0.00	0.60	0.10	0.58	0.20	0.00	0.04	0.73	0.00	0.00	0.84	0.26	3.35
1871-72...	1.00	1.10	0.39	0.26	0.47	1.12	0.16	1.56	0.54	0.22	2.22	4.35	13.39
1872-73...	1.12	0.10	0.00	0.83	0.00	1.16	0.00	0.00	0.15	0.20	0.14	2.52	6.22
1873-74...	0.26	0.00	0.74	3.26	2.65	2.05	1.05	1.48	0.08	0.00	1.88	2.48	15.93
1874-75...	0.00	1.45	3.52	0.66	2.91	0.05	0.30	T.	0.06	0.00	3.33	2.01	14.29
1875-76...	1.35	0.00	0.65	0.13	2.06	0.75	1.00	0.75	0.00	0.98	5.31	12.08	25.06
1876-77...	2.40	2.10	0.15	0.00	0.71	0.51	0.89	0.85	1.70	0.00	0.70	0.41	10.42
1877-78...	2.08	0.45	0.05	2.23	0.14	1.12	1.84	1.75	0.16	0.06	2.10	4.60	16.56
1878-79...	0.98	0.00	0.36	1.24	0.20	0.14	0.00	0.10	0.00	0.00	0.97	0.53	4.52
1879-80...	1.40	0.23	2.40	3.03	1.08	0.13	0.30	0.27	0.00	0.16	1.85	0.97	11.82
1880-81...	0.19	0.57	0.13	1.56	0.07	0.12	2.64	0.97	0.07	T.	1.41	7.53	15.26
1881-82...	1.88	0.20	0.21	0.27	2.72	0.93	0.01	0.08	0.19	1.35	1.25	1.18	10.22
1882-83...	2.16	0.25	1.73	0.07	0.44	1.35	1.63	0.12	0.27	0.04	3.35	1.14	12.55
1883-84...	0.00	0.45	0.00	4.30	0.39	3.59	3.60	1.43	0.72	0.23	0.19	1.24	16.14
1884-85...	0.68	0.84	0.15	4.66	0.00	0.80	2.25	0.69	0.19	0.05	0.84	3.01	14.16
1885-86...	0.03	0.61	1.88	0.52	1.90	1.48	2.09	0.82	0.02	0.01	0.18	3.18	12.72
1886-87...	0.20	0.13	0.55	0.60	0.04	0.78	0.02	0.58	0.60	0.18	3.11	2.96	9.75
1887-88...	4.72	0.00	1.37	0.87	0.96	1.56	1.78	0.43	0.96	0.00	2.21	0.73	15.59
1888-89...	0.56	4.47	2.80	3.15	1.95	0.25	1.66	0.00	0.00	0.02	3.10	0.75	18.71
1889-90...	1.60	1.74	0.08	5.08	1.39	1.97	1.35	0.82	0.01	0.00	1.83	2.30	18.17
1890-91...	0.55	[1.50]	[3.65]	[1.72]	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mean..	1.05	0.76	1.13	1.53	0.96	0.96	1.10	0.62	0.26	0.21	1.82	2.84	13.24

Record of precipitation at Fort McDowell, Maricopa County.

[Latitude 33° 38′, longitude 111° 38′; elevation, 1,250 feet. Authority, United States Hospital Service and Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1866-67...	1.63	0.25	0.06	0.10	0.88	0.16	2.11	0.03	0.00	0.00	2.97	1.18	9.37
1867-68...	1.62	0.03	0.29	5.70	2.70	1.60	0.70	[1.00]	0.00	0.00	4.50	1.70	19.84
1868-69...	3.01	T.	0.01	0.00	0.64	2.60	0.00	0.15	T.	0.10	0.40	1.10	8.01
1869-70...	0.00	0.00	2.15	0.55	T.	0.60	0.65	T.	T.	0.70	0.90	1.98	7.53
1870-71...	0.22	0.40	0.00	T.	0.25	0.40	0.00	0.40	T.	T.	0.16	2.08	3.91
1871-72...	0.20	0.00	1.25	0.20	0.50	0.40	0.00	0.53	0.30	0.31	9.16	7.17	20.02
1872-73...	0.08	T.	0.00	1.56	0.00	1.60	0.90	0.00	0.16	T.	T.	0.56	4.86
1873-74...	0.00	T.	0.21	4.70	3.10	2.86	1.06	1.30	0.30	0.00	1.31	1.99	16.83
1874-75...	0.05	1.11	2.76	1.00	1.40	0.62	T.	0.10	T.	0.00	0.75	0.46	8.25
1875-76...	1.00	0.00	0.00	0.64	0.70	0.10	0.40	T.	0.00	1.00	3.25	1.70	8.79
1876-77...	0.00	T.	0.58	0.00	1.08	2.24	0.44	0.50	1.04	0.00	T.	0.06	5.94
1877-78...	1.52	0.38	T.	2.12	0.04	1.54	1.18	3.20	T.	T.	0.83	1.57	12.41
1878-79...	0.98	0.00	0.99	1.56	0.50	1.22	0.60	0.20	0.00	0.00	T.	0.12	6.17
1879-80...	0.34	0.58	2.14	2.64	1.56	0.38	0.50	0.38	0.00	T.	0.52	0.84	9.88
1880-81...	0.34	[0.40]	0.00	1.69	T.	T.	1.46	0.22	0.12	0.00	1.16	3.38	8.77
1881-82...	0.10	T.	0.80	T.	3.22	0.58	0.00	T.	0.10	0.56	0.40	1.52	7.28
1882-83...	1.34	0.00	1.38	0.00	0.59	0.78	0.42	0.00	0.28	0.04	1.12	1.76	7.71
1883-84...	0.32	0.30	0.06	4.22	0.33	4.37	3.47	0.58	0.45	0.09	0.08	1.25	15.52
1884-85...	3.96	1.38	0.45	4.54	0.00	2.50	0.60	0.00	0.00	0.00	0.00	0.90	14.33
1885-86...	0.90	0.40	1.75	1.25	3.35	1.60	1.50	T.	0.00	[0.00]	0.00	0.62	11.37
1886-87...	T.	0.27	0.44	0.30	0.00	0.86	0.00	0.68	T.	0.00	0.06	1.54	4.15
1887-88...	4.11	0.48	1.82	0.77	0.87	0.72	0.62	0.14	0.40	0.00	0.86	0.17	10.96
1888-89...	0.35	2.82	1.49	3.47	2.85	0.77	0.14	0.09	0.00	0.06	0.62	0.29	12.95
1889-90...	0.61	1.31	0.73	5.31	0.89	1.37	0.96	0.55	0.00	0.00	1.10	1.55	14.38
1890-91...	0.26	1.07	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mean....	0.94	0.45	0.81	1.76	1.06	1.24	0.74	0.42	0.13	0.12	1.26	1.48	10.39

Record of precipitation at Fort Apache, Navajo County.

Latitude 33° 48′, longitude 109° 57′; elevation, 5,050 feet. Authority, Signal Service and United States Hospital Service.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1875-76...	.....	.....	.....	.....	0.92	1.72	2.02	0.08	0.26	1.02	5.20	2.52	.....
1876-77...	2.00	2.44	1.34	0.22	0.36	0.94	0.72	0.96	1.15	0.00	3.11	1.20	14.44
1877-78...	0.99	0.81	0.19	2.07	0.18	1.35	2.41	1.77	0.18	0.79	8.76	9.33	28.83
1878-79...	0.76	0.00	1.94	1.14	1.89	1.17	0.03	0.12	0.00	0.05	3.92	3.06	14.08
1879-80...	1.52	2.64	1.77	2.41	1.31	0.95	0.80	0.46	0.00	0.46	5.83	1.44	19.59
1880-81...	0.55	0.56	0.03	2.38	0.20	1.17	2.45	1.53	0.35	T.	5.63	8.31	23.16
1881-82...	5.41	4.68	0.85	0.54	2.82	2.85	1.09	0.91	0.94	3.27	4.79	7.36	35.51
1882-83...	1.02	T.	2.34	0.23	0.85	2.46	2.03	0.22	0.86	0.02	5.46	4.26	19.75
1883-84...	0.60	1.39	0.02	3.48	0.68	3.43	4.44	1.67	1.31	2.35	0.14	5.59	25.10
1884-85...	1.50	2.02	0.82	5.52	0.52	1.00	2.05	0.52	1.12	0.82	2.60	3.16	21.65
1885-86...	0.44	0.38	1.56	1.41	3.90	2.73	1.06	0.91	0.00	0.19	1.90	4.75	19.23
1886-87...	3.16	1.66	0.56	0.24	0.59	2.16	0.04	0.81	0 15	1.70	3.29	3.92	18.28
1887-88...	2.23	0.55	1.83	0.57	1.42	1.83	2.92	0.71	0.71	T.	3.24	[1.00]	17.01
1888-89...	0.32	1.23	2.63	2.88	2.24	0.88	1.85	0.47	0.00	0.11	2.67	2.87	18.15
1889-90...	1.02	0.46	0.55	3.98	2.26	2.40	0.82	1.39	0.00	0.00	5.00	4.44	22.32
1890-91...	2.37	2.17	2.85	3.02	1.65	4.10	0.85	T.	0.36	T.	2.72	1.22	21.31
1891-92...	1.81	0.00	0.00	0.65	0.65	2.29	2.22	1.36	0.36	0.15	1.33	1.30	12.12
1892-93...	1.23	0.55	0.57	0.69	0.28	1.10	2.45	0.00	2.18	0.00	2.57	3.43	15.05
1893-94...	2.65	0.04	0.28	0.10	1.24	0.96	1.36	0.19	0.79	0.00	1.27	5.01	13.89
1894-95...	1.32	2.47	0.00	2.81	1.89	0.72	0.02	T.	1.00	0.01	0.74	5.44	16.42
1895-96...	1.68	3.02	2.39	1.12	0.16	0.33	0.86	0.34	0.00	0.52	4.31	4.36	19.09
Mean..	1.63	1.35	1.13	1.77	1.23	1.74	1.55	0.69	0.56	0.55	3.55	4.00	19.75

Record of precipitation at Pinal Ranch, Pinal County.

[Latitude 33° 25′, longitude 110° 58′; elevation, 4,400 feet. Authority, Irion and Craig.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1891-92	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.00	0.81	.....
1892-93	0.15	0.90	0.43	0.99	0.92	1.57	5.21	0.00	1.44	0.00	2.86	3.69	18.16
1893-94	4.13	0.00	1.66	0.83	1.23	1.81	1.93	0.00	0.14	0.00	1.63	2.87	16.23
1894-95	0.32	1.19	0.00	7.77	7.28	1.06	0.31	0.00	0.36	0.00	0.63	5.88	24.80
1895-96	2.04	4.78	5.33	1.52	1.10	0.18	1.05	0.50	0.00	0.24	4.04	2.90	23.69
1896-97	3.47	3.42	2.35	1.13	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mean	2.02	2.06	1.95	2.45	2.63	1.16	2.13	0.13	0.48	0.06	1.83	3.23	20.46

Record of precipitation at Phœnix, Maricopa County.

[Latitude 33° 28′, longitude 112° 00′; elevation, 1,068 feet. Authority, Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1875-76	.....	.....	.....	.....	.....	0.82	0.27	0.00	0.00	.....	.....	[1.00]	.....
1876-77	0.90	0.72	0.00	0.00	0.60	1.63	0.31	0.00	0.00	0.00	[1.00]	0.02	5.18
1877-78	1.11	0.04	0.03	0.43	0.07	1.07	0.96	1.25	0.04	0.00	2.40	1.63	9.03
1878-79	0.19	0.00	0.27	0.64	0.07	0.75	0.33	0.07	0.00	0.00	0.54	0.67	3.53
1879-80	0.69	0.27	1.66	1.35	1.16	0.38	0.26	0.15	0.00	0.49	1.18	0.72	8.31
1880-81	0.67	0.20	0.00	1.61	0.00	0.20	1.46	1.10	0.12	0.00	2.03	2.19	9.58
1881-82	1.04	0.25	0.36	0.16	1.62	0.17	0.00	0.00	0.00	0.37	0.32	1.81	6.10
1882-83	1.25	0.10	1.30	0.00	0.83	1.27	1.16	T.	0.44	0.00	0.07	0.07	6.49
1883-84	0.00	0.20	0.00	3.36	0.16	2.46	2.14	0.40	0.01	0.15	0.07	1.84	10.79
1884-85	1.50	1.12	0.24	2.74	0.00	0.47	0.33	0.00	0.65	0.04	0.18	0.71	7.98
1885-86	0.07	0.09	0.91	0.32	1.32	1.25	1.86	0.29	0.00	0.00	0.05	0.59	6.75
1886-87	0.45	0.58	0.32	0.07	0.00	0.28	T.	0.75	0.06	0.00	.....	.....	.....
1887-88	.....	.....	.....	[0.50]	.....	.....	.....	0.01	0.30	0.00	0.13	0.27	.....
1888-89	0.23	[2.80]	1.10	[3.00]	.....	.....	.....	.....	0.00	0.12	0.66	1.77	.....
1889-90	0.39	0.99	0.77	3.38	0.95	0.52	1.18	0.51	0.00	.....	.....	.....	.....
1891-92	.....	.....	0.00	0.13	1.85	2.20	0.60	0.70	0.15	0.00	0.00	0.00	.....
1892-93	0.00	0.00	0.00	0.00	0.00	0.00	0.46	0.00	1.00	0.00	3.20	[1.42]	6.08
1893-94	0.00	0.00	0.60	1.00	0.00	0.70	0.62	0.00	0.07	0.00	0.97	0.79	4.75
1894-95	0.15	0.77	0.00	1.43	.....	.....	.....	0.00	.....	.....	.....	.....	.....
1895-96	.....	.....	1.22	0.07	0.48	0.00	0.28	0.00	0.00	0.00	3.66	1.05	.....
Mean	0.54	0.51	0.48	1.44	0.57	0.83	0.72	0.29	0.15	0.07	1.03	0.97	7.60

Record of precipitation at Fort Bowie, Cochise County.

[Latitude 32° 12′, longitude 109° 20′; elevation, 4,781 feet. Authority, United States Hospital Service and Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1866-67	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	2.67	.....
1867-68	1.70	T.	0.50	1.64	2.39	1.10	0.00	0.70	0.50	0.00	7.15	2.40	18.08
1868-69	3.15	T.	0.70	0.00	0.10	3.50	0.39	0.15	0.00	0.40	1.30	5.60	15.29
1869-70	0.20	T.	1.45	0.15	0.30	0.69	0.50	T.	0.00	0.60	4.50	5.42	13.81
1870-71	1.00	0.00	T.	1.00	0.50	[1.00]	[0.50]	[0.60]	0.18	0.60	7.90	2.30	15.58
1871-72	1.00	0.70	0.90	[1.25]	[0.40]	[0.50]	0.00	0.25	0.20	1.04	1.67	3.36	11.27
1872-73	0.77	T.	0.15	2.95	0.00	1.16	2.22	T.	1.09	0.14	0.50	1.34	10.32
1873-74	0.01	0.03	1.12	2.02	2.33	5.40	1.50	0.35	0.00	T.	2.66	3.12	18.54
1874-75	0.06	1.40	1.45	0.46	1.35	1.20	0.13	0.13	T.	0.65	4.22	1.77	12.82

Record of precipitation at Fort Bowie, Cochise County—Continued.

[Latitude 32° 12′, longitude 109° 20′; elevation, 4,781 feet. Authority, United States Hospital Service and Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1875-76...	3.19	0.00	0.25	0.83	0.60	0.45	0.48	T.	T.	2.05	4.55	4.00	16.40
1876-77...	1.95	0.73	0.40	0.00	0.14	2.70	0.12	0.14	0.90	0.00	1.24	0.18	8.50
1877-78...	1.16	0.00	0.00	2.04	[0.50]	0.50	2.83	1.00	0.20	0.20	4.92	7.44	20.79
1878-79...	0.07	0.07	1.50	1.09	3.00	0.63	0.40	0.02	0.00	0.00	1.01	0.20	7.99
1879-80...	2.00	0.60	0.10	0.50	0.25	1.40	1.45	0.15	0.00	1.50	4.80	0.97	13.72
1880-81...	1.35	0.70	0.05	0.82	0.00	0.20	0.79	0.05	0.10	0.06	5.53	5.16	14.81
1881-82...	2.27	1.15	0.58	0.03	0.90	1.15	1.51	0.26	0.71	1.39	3.58	4.84	18.37
1882-83...	1.51	[0.00]	1.79	0.35	1.49	1.33	2.84	0.00	1.50	0.33	2.21	1.73	15.08
1883-84...	0.72	0.20	0.39	1.12	3.14	4.96	2.63	0.00	0.23	0.12	0.65	2.44	16.60
1884-85...	0.62	3.58	0.42	6.41	0.53	1.81	2.19	0.00	0.19	0.66	1.83	2.19	20.43
1885-86...	0.44	0.00	1.42	1.74	4.24	4.88	4.48	0.07	0.01	4.21	2.24	2.49	26.22
1886-87...	1.26	0.36	0.74	0.15	0.13	2.11	0.00	0.23	T.	1.30	4.49	5.51	16.28
1887-88...	2.71	1.01	1.10	1.94	1.11	1.50	1.92	T.	0.46	0.53	2.50	1.37	16.15
1888-89...	0.21	1.89	1.95	2.12	1.38	1.62	1.58	T.	0.09	0.09	2.65	0.20	13.78
1889-90...	3.37	0.74	T.	0.51	0.78	0.23	0.03	0.59	0.00	T.	4.97	4.06	15.28
1890-91...	1.74	1.60	0.61	2.45	0.69	2.18	0.65	0.00	1.38	T.	0.28	1.00	12.58
1891-92...	0.61	0.00	0.00	1.26	0.81	3.36	1.62	0.41	0.00	0.50	1.12	2.65	12.34
1892-93...	0.00	1.80	0.30	0.60	0.40	0.80	2.70	0.00	0.30	0.00	3.69	3.41	14.00
1893-94...	1.06	0.04	0.07	0.25	0.65	2.55	1.07	0.01	T.	T.	1.07	4.80	11.57
1894-95...	1.06	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mean..	1.26	0.59	0.66	1.25	1.04	1.81	1.28	0.19	0.30	0.61	3.08	3.95	16.02

Record of precipitation at Wilcox, Cochise County.

[Latitude 32° 20′, longitude 109° 42′; elevation, 4,164 feet. Authority, Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1880-81...	.....	0.04	0.00	0.40	0.02	0.00	2.95	T	0.00	[0.00]	3.97	5.17	12.55
1881-82...	0.00	0.00	0.00	0.00	[0.50]	1.15	0.90	0.00	0.00	[0.90]	0.11	3.46	6.22
1882-83...	1.56	0.00	0.58	0.32	1.25	0.31	0.41	0.00	0.33	0.03	1.56	3.15	9.50
1883-84...	0.04	0.30	0.36	0.99	0.80	1.61	1.75	0.00	0.00	0.04	1.17	1.54	8.60
1884-85...	0.14	3.59	0.25	3.49	0.05	0.63	1.52	0.03	[0.20]	0.34	1.78	2.10	14.12
1885-86...	1.11	0.00	0.56	0.19	[3.00]	[1.00]	0.15	0.01	0.00	T.	0.37	2.14	8.53
1886-87...	1.68	0.36	0.58	0.08	T.	1.83	0.00	0.03	0.48	0.47	3.82	5.31	14.64
1887-88...	2.96	0.45	0.22	0.92	0.36	1.21	1.13	0.03	0.14	0.08	3.68	0.42	11.60
1888-89...	0.50	1.15	1.86	1.37	1.31	0.90	1.03	0.04	0.00	0.13	4.91	0.97	14.20
1889-90...	2.91	0.83	T.	0.62	1.61	0.35	0.22	0.63	0.00	0.14	2.64	5.20	15.15
1890-91...	1.97	0.54	0.43	0.72	0.54	2.45	0.26	0.00	0.87	0.07	T.	2.10	9.95
1891-92...	0.22	0.00	0.00	0.85	0.05	1.45	0.84	0.25	1.02	2.00	0.97	0.94	8.59
1892-93...	0.32	0.00	0.00	0.17	0.00	0.10	0.79	0.00	0.50	0.00	1.74	1.03	4.65
1893-94...	0.93	0.00	0.00	0.00	0.50	1.37	0.77	0.00	0.00	0.00	0.00	1.52	5.09
1894-95...	0.27	0.78	0.00	0.67	0.11	0.00	0.00	0.00	0.77	0.00	1.92	3.06	7.58
1895-96...	0.11	0.08	1.59	0.40	0.27	1.03	0.05	0.00	0.00	0.00	1.46	1.77	6.76
Mean..	0.98	0.51	0.40	0.70	0.65	0.96	0.74	0.06	0.27	0.26	1.88	2.49	9.90

Record of precipitation at Fort Grant, Graham County.

[Latitude 32° 36′, longitude 109° 53′; elevation, 4,860 feet. Authority, Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1872-73...	.....	.....	.....	.....	0.00	0.10	1.00	0.00	0.50	1.40	1.70	5.20	9.90
1873-74...	2.50	0.46	3.38	1.75	1.58	2.87	2.45	0.58	0.07	0.00	2.70	2.01	20.35
1874-75...	0.00	1.47	0.30	3.78	2.48	1.44	1.95	1.52	0.00	0.50	7.02	1.08	21.54
1875-76...	4.59	0.01	0.20	0.12	0.26	0.24	0.44	.....	.....	0.65	5.27	7.41	.....
1876-77...	1.99	2.86	1.00	[1.42]	0.17	1.50	0.30	0.42	0.66	0.00	0.94	0.60	11.86
1877-78...	2.88	0.50	0.00	2.16	0.23	0.50	0.37	0.18	0.00	0.32	6.44	4.93	18.51
1878-79...	0.20	0.00	1.90	1.39	1.38	0.47	0.85	0.07	0.00	0.08	2.59	1.12	10.05
1879-80...	2.18	1.83	0.87	1.38	0.60	0.48	0.85	0.08	0.00	1.32	5.63	3.73	18.95
1880-81...	1.01	0.47	0.00	1.57	0.05	0.33	0.89	0.84	0.26	T.	5.53	5.47	16.42
1881-82...	3.84	1.02	0.08	0.65	0.86	1.26	1.84	0.07	0.81	1.47	2.62	4.73	19.25
1882-83...	0.80	0.00	0.79	0.17	1.21	1.40	1.27	0.08	1.16	1.26	2.90	3.07	14.06
1883-84...	0.42	1.21	0.11	1.44	1.12	4.62	3.87	0.47	0.81	1.20	0.67	2.41	18.35
1884-85...	0.98	3.06	0.53	5.93	0.31	1.02	1.40	0.04	0.25	0.73	0.93	1.58	16.76
1885-86...	0.81	0.03	1.30	0.81	2.46	1.29	0.53	0.30	0.04	0.57	2.79	3.40	14.33
1886-87...	3.49	0.57	0.10	0.09	0.11	2.58	T.	0.36	0.16	0.85	9.00	6.20	23.51
1887-88...	4.20	0.37	0.28	0.21	0.12	0.44	0.83	0.50	0.18	0.02	4.27	0.52	11.94
1888-89...	0.78	1.19	3.67	1.68	1.99	1.28	1.04	0.13	T.	1.06	3.57	1.35	17.74
1889-90...	0.69	0.94	0.16	1.11	1.58	0.46	0.46	0.92	0.01	0.20	3.23	4.54	14.30
1890-91...	0.69	1.62	0.16	2.01	0.82	3.78	0.28	0.00	1.40	0.10	1.19	2.25	14.30
1891-92...	1.21	0.00	0.00	1.18	0.96	1.59	1.66	0.64	0.35	0.00	0.86	1.00	9.45
1892-93...	0.11	0.46	0.12	0.15	0.56	0.59	1.26	0.00	0.58	0.00	4.24	2.00	10.07
1893-94...	3.87	T	0.40	0.35	0.38	3.43	0.66	0.13	0.37	0.00	2.55	1.98	14.12
1894-95...	0.14	1.10	0.00	2.79	1.65	0.37	0.02	0.07	0.30	0.14	1.09	4.02	11.69
1895-96...	1.69	1.21	2.05	0.61	0.29	0.50	0.34	0.26	0.00	0.90	1.88	2.68	12.41
Mean..	1.70	0.89	0.76	1.42	0.88	1.36	1.02	0.33	0.34	0.53	3.32	3.05	15.45

Record of precipitation at Fort Thomas, Graham County.

[Latitude 33° 04′, longitude 109° 51′; elevation, 2,700 feet. Authority, United States Hospital Service and Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1879-80...	.....	.....	.....	.....	.....	.....	.....	0.06	0.00	0.55	0.87	2.49	.....
1880-81...	0.55	0.18	0.03	1.27	0.03	0.13	1.21	0.63	0.07	0.00	4.18	2.49	10.77
1881-82...	1.55	0.40	0.32	0.40	0.33	1.01	0.70	0.02	0.47	1.26	0.88	2.48	9.82
1882-83...	0.28	0.00	0.77	0.46	1.23	1.54	1.33	0.00	0.79	0.00	1.85	2.52	10.77
1883-84...	T.	0.52	0.00	1.07	0.45	2.94	3.21	0.72	0.60	0.52	0.36	2.04	12.43
1884-85...	0.91	0.69	0.56	5.16	0.03	1.00	0.75	0.14	0.09	0.18	2.93	2.46	14.90
1885-86...	0.02	0.01	0.38	0.71	2.16	1.40	0.44	0.24	0.00	0.00	0.10	4.02	9.48
1886-87...	1.18	1.12	0.16	0.04	0.09	0.84	0.00	0.31	2.73	0.35	3.78	2.53	13.13
1887-88...	3.87	0.28	0.52	1.05	0.65	1.06	1.78	0.37	0.23	0.00	1.88	0.64	12.33
1888-89...	0.55	2.80	1.72	1.66	1.47	1.35	0.96	0.10	0.00	T.	3.45	1.40	15.46
1889-90...	0.38	0.26	0.34	1.18	1.92	0.49	0.45	1.21	0.00	T.	2.02	4.11	12.36
1890-91...	0.75	1.30	0.69	0.99	0.72	2.98	0.40	0.00	1.61	0.18	.....	.....	.....
Mean..	0.91	0.69	0.50	1.27	0.83	1.34	1.02	0.32	0.55	0.25	2.03	2.47	12.18

Record of precipitation at San Carlos, Gila County.

[Latitude 33° 12′, longitude 110° 27′; elevation, 3,456 feet. Authority, Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1880-81...	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.00	4.13	5.93	.....
1881-82...	1.94	0.93	0.06	0.52	1.24	0.93	0.55	0.00	0.71	1.09	1.98	6.05	16.00
1882-83...	0.58	0.00	1.58	0.66	1.60	2.07	0.71	0.00	0.53	0.00	2.48	1.11	11.32
1883-84...	0.11	1.13	0.00	2.47	1.00	3.83	3.97	0.84	0.32	0.49	0.37	1.24	15.77
1884-85...	0.83	1.49	0.55	5.48	0.05	1.39	1.28	0.03	0.22	0.47	1.25	1.22	14.26
1885-86...	0.34	0.34	0.70	0.90	2.88	1.29	0.82	0.14	0.00	0.00	0.03	3.49	10.93
1886-87...	0.87	0.46	0.46	0.00	T.	1.12	0.00	0.23	0.06	0.31	2.49	1.56	7.56
1887-88...	0.88	0.08	[0.50]	1.45	0.52	1.06	1.98	0.00	0.10	0.00	2.10	0.40	8.99
1888-89...	0.63	1.73	1.76	2.84	1.62	1.33	2.15	0.25	0.00	T.	1.83	0.87	15.01
1889-90...	2.05	0.60	0.40	2.30	2.11	1.66	1.08	1.31	0.00	0.00	2.25	3.41	17.12
1890-91...	0.89	1.22	2.12	2.68	0.75	5.25	0.47	0.00	0.77	0.00	0.57	1.00	15.67
1891-92...	0.75	0.00	0.00	1.44	1.80	3.51	1.22	1.03	0.08	0.00	1.30	1.90	13.03
1892-93...	0.00	0.65	0.34	0.22	0.50	0.55	2.96	0.00	0.67	0.00	0.80	3.78	10.47
1893-94...	2.56	0.00	0.34	0.37	0.63	1.37	1.14	0.11	0.31	0.00	0.81	2.06	9.70
1894-95...	0.09	1.05	0.00	2.58	2.16	0.45	0.18	0.00	0.04	0.05	0.32	2.39	9.31
1895-96...	1.94	3.01	3.42	0.45	0.43	0.04	0.50	T.	0.00	T.	3.78	0.88	14.45
Mean..	0.96	0.85	0.82	1.62	1.15	1.72	1.26	0.26	0.25	0.15	1.66	2.33	13.03

Record of precipitation at Benson, Cochise County.

[Latitude 32° 00′, longitude 110° 22′; elevation, 3,580 feet. Authority, Pacific Railway System.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1880-81...	[0.71]	0.00	0.00	[1.50]	0.00	0.00	0.75	0.00	0.00	0.02	2.17	4.33	9.48
1881-82...	0.99	0.34	0.00	0.00	0.40	1.20	0.00	0.00	0.00	0.86	2.00	3.58	9.37
1882-83...	0.65	0.00	0.80	0.15	0.65	0.63	2.08	0.00	0.42	0.16	2.97	2.78	11.29
1883-84...	0.10	0.21	0.07	0.50	0.20	0.63	1.20	T.	0.00	0.00	0.70	0.27	3.88
1884-85...	0.30	2.89	T.	2.50	0.05	0.95	0.07	0.00	0.00	0.75	0.58	1.44	9.53
1885-86...	0.14	0.00	0.09	0.17	0.79	0.67	0.08	0.00	0.00	0.00	1.44	2.68	6.06
1886-87...	0.17	0.25	0.00	0.19	0.00	0.34	0.00	T.	0.08	0.00	1.49	2.39	4.91
1887-88...	2.92	0.45	0.37	0.15	0.04	0.00	0.30	0.00	0.37	0.00	2.44	1.66	8.70
1888-89...	0.05	0.84	1.11	1.03	0.93	0.07	0.63	0.00	0.00	0.63	2.16	0.94	8.39
1889-90...	1.04	0.05	0.00	1.33	1.94	0.00	0.00	0.23	0.00	0.52	[2.50]	4.81	12.42
1890-91...	1.44	0.41	0.50	1.48	0.38	1.31	0.15	0.00	[0.00]	[0.25]	1.19	1.81	8.92
1891-92...	0.34	0.00	0.00	0.38	0.40	1.30	0.40	0.42	0.00	0.00	0.00	0.07	3.31
1892-93...	0.03	0.00	0.00	[0.63]	0.00	0.00	[0.92]	0.00	0.76	0.00	2.88	3.03	8.25
1893-94...	0.12	0.00	0.00	0.00	T.	1.50	0.40	0.00	0.00	0.10	1.65	2.03	5.80
1894-95...	0.95	0.00	0,00	0.74	0.00	0.00	[0.47]	0.00	1.00	0.00	0.13	1.20	4.49
1895-96...	1.40	0.00	0.00	0.00	0.10	0.00	0.12	0.00	0.00	0.00	0.00	0.60	4.77
Mean..	0.71	0.34	0.18	0.63	0.36	0.54	0.47	0.04	0.16	0.21	1.68	2.10	7.42

Record of precipitation at Tucson, Pima County.

[Latitude 32° 14′, longitude 110° 54′; elevation, 2,404 feet. Authority, Pacific Railway System and E. L. Wetmore.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1875-76...	.....	.....	0.18	0.82	0.37	0.25	1.22	0.00	0.00	0.29	3.71	4.19	.....
1876-77...	2.28	0.96	0.75	0.00	0.19	2.53	0.20	0.57	0.41	0.00	3.04	0.02	10.95
1877-78...	2.44	0.46	0.00	2.91	0.22	1.00	1.77	0.52	0.00	0.65	5.72	4.71	20.40
1878-79...	0.08	0.00	1.31	0.68	2.02	0.94	0.83	0.02	0.00	0.01	0.84	1.76	8.49
1879-80...	0.74	0.94	0.60	3.31	0.56	0.15	0.41	0.04	0.00	T.	1.62	1.28	9.65
1880-81...	1.89	0.09	0.00	0.57	0.05	0.25	1.17	0.62	0.04	0.00	5.69	3.92	14.29
1881-82...	2.37	0.62	0.00	0.19	1.75	1.64	0.72	0.05	0.01	0.99	2.63	6.32	17.29
1882-83...	0.32	0.00	1.12	0.04	1.27	0.51	1.14	T.	0.35	0.08	2.20	1.40	8.43
1883-84...	0.10	0.65	0.02	0.06	0.83	2.59	1.91	0.17	0.23	0.23	0.32	1.15	8.26
1884-85...	0.30	2.24	0.34	4.72	0.00	0.42	0.40	0.00	0.00	0.13	1.00	1.76	11.31
1885-86...	0.12	0.00	0.42	1.01	1.61	0.36	0.87	0.06	0.00	0.00	1.06	2.47	7.98
1886-87...	[1.00]	0.31	0.45	0.40	0.00	0.85	0.00	0.38	0.32	0.26	5.08	1.25	10.30
1887-88...	2.08	1.72	0.74	0.27	0.73	0.57	1.03	T.	0.32	0.55	1.58	0.92	10.51
1888-89...	0.10	0.78	2.06	1.96	1.74	1.06	1.98	0.18	T.	0.30	5.66	2.06	17.88
1889-90...	3.12	0.36	0.32	1.59	1.27	0.76	0.29	0.10	0.00	0.00	2.37	5.13	15.31
1890-91...	1.44	0.65	0.83	1.32	0.12	2.08	0.17	0.00	0.18	0.22	0.70	2.26	9.97
1891-92...	0.65	0.00	0.00	0.23	1.66	2.54	1.01	0.26	0.36	0.21	2.19	1.84	10.95
1892-93...	0.61	0.32	0.00	0.25	0.27	0.88	1.16	T.	1.09	0.00	2.44	5.65	12.67
1893-94...	0.96	T.	0.40	0.41	0.11	1.04	1.17	T.	0.05	T.	1.60	1.01	6.75
1894-95...	0.12	0.31	0.00	1.88	0.56	T.	0.00	T.	0.09	0.02	0.11	5.35	8.44
1895-96...	0.75	0.68	4.30	0.08	0.53	0.10	0.27	0.12	T.	0.19	3.45	1.25	11.72
Mean..	1.07	0.55	0.66	1.08	0.76	0.98	0.84	0.15	0.16	0.20	2.52	2.65	11.62

Record of precipitation at Casa Grande, Pinal County.

[Latitude 32° 54′, longitude 111° 40′; elevation, 1,398 feet. Authority, Pacific Railway System.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1880-81...	[0.45]	0.05	0.00	[1.00]	0.00	0.00	[1.00]	0.73	0.00	0.00	0.00	T.	3.23
1881-82...	0.00	0.00	0.00	0.00	[2.00]	[0.80]	0.00	0.00	0.00	[0.10]	0.00	0.00	2.90
1882-83...	0.00	0.00	[0.35]	0.00	0.00	0.00	0.00	0.00	0.24	0.00	[1.00]	0.81	2.40
1883-84...	0.00	0.10	0.00	0.86	0.75	[1.00]	1.08	0.00	0.00	0.00	0.00	2.37	6.16
1884-85...	0.00	1.31	0.00	3.20	0.00	0.30	0.10	0.00	0.00	0.00	0.75	0.64	6.30
1885-86...	0.00	0.00	0.23	0.00	0.90	[1.25]	0.74	0.09	0.00	0.00	0.33	1.46	5.00
1886-87...	0.00	0.00	0.35	0.00	0.00	0.40	0.00	0.30	0.20	0.40	1.07	0.97	3.69
1887-88...	1.99	0.95	1.28	0.15	0.61	0.00	0.45	0.00	[0.10]	0.00	0.28	0.00	5.81
1888-89...	0.41	[1.00]	0.70	0.75	[1.00]	0.00	0.50	0.10	0.00	0.00	0.00	0.00	4.46
1889-90...	0.50	0.80	0.10	1.25	0.30	0.61	0.41	0.38	0.00	0.00	1.38	3.41	9.14
1890-91...	0.96	0.38	2.00	0.87	0.65	1.90	0.00	0.00	0.00	0.00	0.90	0.00	7.66
1891-92...	0.00	0.00	0.00	0.17	3.25	2.35	0.65	0.00	0.34	0.00	0.23	0.64	7.63
1892-93...	0.00	0.15	0.00	1.14	0.06	0.00	1.87	0.00	0.07	0.00	1.72	0.95	5.96
1893-94...	0.00	0.00	0.00	0.25	0.00	0.10	0.62	0.00	0.07	0.00	0.67	0.81	2.52
1894-95...	0.89	0.13	0.00	2.53	0.45	0.00	0.00	0.00	0.00	0.00	0.35	1.30	5.65
1895-96...	2.00	1.60	0.60	.....	0.65	0.00	0.10	0.00	0.00	0.00	.....	0.88	.....
Mean..	0.45	0.40	0.35	0.81	0.66	0.54	0.47	0.10	0.06	0.03	0.58	0.89	5.34

Record of precipitation at Maricopa, Pinal County.

[Latitude 33° 05′, longitude 112° 00′; elevation, 1,190 feet. Authority, Pacific Railway System and Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1875-76...	.....	.....	0.00	0.00	0.72	0.27	0.39	0.00	0.00	0.45	0.44	1.09	.....
1876-77...	0.00	0.10	0.41	0.00	0.08	1.57	0.30	0.03	0.41	0.00	1.26	0.00	4.16
1877-78...	1.07	0.00	0.01	1.54	0.00	1.01	.....	.....	.....	.....	.....	.....	.....
1878-79...	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.00	0.10	1.81	.....
1879-80...	0.38	0.04	0.85	0.80	1.45	0.16	0.00	0.75	0.00	0.00	0.00	0.00	4.43
1880-81...	0.50	0.00	0.00	0.50	0.00	0.00	0.88	0.00	0.00	0.00	0.00	1.47	3.35
1881-82...	0.50	0.00	0.00	0.00	T.	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.88
1882-83...	0.00	0.00	0.00	0.00	1.34	0.00	0.00	0.00	0.00	0.00	0.50	3.57	5.41
1883-84...	0.30	0.00	0.00	1.96	0.38	0.74	2.83	0.51	0.01	0.32	0.53	0.86	8.44
1884-85...	1.10	1.51	0.20	2.97	0.00	0.45	0.15	0.00	0.18	0.04	0.48	0.92	8.00
1885-86...	T.	0.00	0.56	0.19	1.32	1.65	1.71	0.06	0.00	0.00	0.16	0.08	5.73
1886-87...	0.06	0.76	0.21	0.11	0.00	0.17	T.	0.51	0.31	0.03	0.43	0.50	3.09
1887-88...	1.00	0.28	1.13	0.00	0.00	0.12	0.48	0.00	0.00	0.00	0.80	0.22	4.03
1888-89...	0.35	0.52	0.75	0.70	0.85	0.15	1.19	0.00	0.00	0.00	0.55	0.90	5.96
1889-90...	0.90	1.20	0.83	3.00	0.00	0.22	1.02	0.00	0.00	0.00	0.10	4.29	11.56
1890-91...	0.15	0.07	0.31	2.47	0.02	2.33	0.00	0.01	0.00	0.00	0.13	0.39	5.88
1891-92...	0.13	0.00	0.00	0.00	1.55	2.44	0.50	0.40	0.14	0.00	0.62	0.25	6.03
1892-93...	0.15	0.00	0.00	0.00	1.26	0.00	1.14	0.00	0.64	0.00	0.68	0.50	4.37
1893-94...	2.08	0.00	0.30	0.00	0.32	0.12	0.50	0.00	0.00	0.00	0.38	1.96	5.66
1894-95...	0.35	0.50	0.00	2.44	0.61	0.00	0.00	0.00	0.00	0.00	0.93	0.85	5.68
1895-96...	1.10	1.10	1.48	0.00	0.68	0.00	0.22	0.00	0.00	0.03	1.18	0.27	6.06
Mean..	0.53	1.01	0.35	0.83	0.52	0.57	0.60	0.12	0.81	0.04	0.46	1.01	6.85

Record of precipitation at Texas Hill, Yuma County.

[Latitude 32° 44′, longitude 113° 38′; elevation, 355 feet. Authority, Pacific Railway System.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July	Aug.	Total.
1879-80...	0.05	0.55	0.43	0.47	0.23	0.00	0.00	0.06	0.00	0.00	0.00	0.00	1.79
1880-81...	0.35	0.00	0.00	0.34	0.00	0.00	0.24	0.56	0.00	0.00	0.03	0.24	1.76
1881-82...	0.12	2.50	0.00	0.18	1.87	0.00	0.00	0.00	0.00	0.00	0.00	0.53	5.20
1882-83...	[0.00]	0.05	0.12	0.00	0.19	0.14	0.20	0.03	0.00	0.00	0.68	0.70	2.11
1883-84...	0.00	0.09	[0.00]	1.05	0.22	1.21	1.75	0.28	0.28	0.00	0.00	0.00	4.88
1884-85...	0.02	0.00	0.00	1.26	0.00	0.04	0.02	0.00	0.00	0.00	0.00	2.25	3.59
1885-86...	0.00	0.00	0.32	0.00	0.93	1.15	0.00	0.20	0.00	0.00	T.	0.95	3.55
1886-87...	0.00	1.50	0.00	0.00	0.00	0.01	0.00	T.	0.00	0.00	T.	T.	1.51
1887-88...	2.89	0.00	1.40	0.05	0.25	0.00	0.63	0.00	0.00	0.00	0.08	0.00	5.30
1888-89...	[0.30]	1.94	[0.50]	1.29	2.65	0.00	0.12	0.00	0.00	0.00	T.	0.00	6.80
1889-90...	0.00	0.10	0.05	0.62	0.00	0.40	0.00	0.00	0.00	0.00	0.10	[0.50]	1.77
1890-91...	0.10	0.03	0.10	1.28	0.00	2.50	0.00	0.00	0.00	0.00	0.11	0.65	4.77
1891-92...	0.20	0.00	0.00	[0.05]	1.64	.....	.....	.....	0.00	0.00	0.00	0.00	.....
1892-93...	0.00	0.00	0.00	0.00	0.00	0.00	[1.50]	0.00	0.00	0.00	0.40	0.00	1.90
1893-94...	0.00	0.00	0.00	0.00	.....	.....	.....	.....	.....	.....	.....	.....	.....
1894-95...	.....	.....	.....	.....	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.....
1895-96...	0.00	0.00	0.10	0.00	0.00	0.00	0.75	0.00	0.00	0.00	1.15	1.20	3.20
Mean..	0.25	0.42	0.18	0.41	0.50	0.36	0.35	0.08	0.02	0.00	0.16	0.43	3.16

Record of precipitation at Yuma, Yuma County.

[Latitude 32° 44′, longitude 114° 36′; elevation, 141 feet. Authority, Weather Bureau.]

Year.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Total.
1875-76...	[0.17]	T.	0.00	0.00	0.44	0.46	0.04	0.00	0.00	0.00	0.00	0.00	1.11
1876-77...	0.00	0.00	0.00	0.00	0.09	1.72	0.00	0.00	0.06	0.00	0.50	0.06	2.43
1877-78...	T.	0.00	0.00	1.23	0.00	0.06	0.13	0.02	0.00	0.00	0.55	1.59	3.58
1878-79...	0.37	0.00	0.02	0.14	0.59	1.21	0.48	0.15	0.00	0.00	0.00	0.00	2.96
1879-80...	0.11	0.33	0.15	0.27	T.	T.	0.00	T.	0.00	0.00	T.	T.	0.86
1880-81...	T.	T.	0.00	0.74	0.00	0.00	T.	0.55	0.00	T.	0.20	0.08	1.57
1881-82...	0.05	T.	0.00	0.10	1.35	0.01	0.00	0.00	0.00	0.05	0.20	0.03	1.79
1882-83...	0.04	0.01	0.09	0.00	0.96	0.68	T.	T.	0.00	0.00	0.31	0.22	2.31
1883-84...	0.13	0.05	0.00	[1.61]	T.	1.58	1.48	0.07	0.44	T.	0.01	0.32	5.69
1884-85...	T.	T.	T.	1.96	T.	0.02	T.	0.07	T.	0.00	0.05	0.86	2.96
1885-86...	0.00	0.00	1.71	0.01	1.06	0.08	0.33	0.31	0.00	0.00	T.	2.23	5.73
1886-87...	0.00	1.11	0.23	0.00	0.00	T.	0.00	0.20	T.	0.01	T.	T.	1.55
1887-88...	1.09	0.02	2.43	0.15	0.18	0.05	0.05	T.	0.00	0.00	0.04	T.	4.01
1888-89...	0.01	0.99	0.68	0.95	1.12	0.06	0.24	0.00	0.00	T.	T.	0.25	4.30
1889-90...	0.00	0.59	T.	2.43	T.	0.86	T.	0.37	0.43	0.00	0.00	0.67	5.35
1890-91...	0.64	.....	.....	.....	0.00	2.53	T.	0.00	T.	0.00	0.04	0.05	.....
1891-92...	T.	0.00	0.00	0.05	1.85	0.87	0.52	T.	0.05	0.00	0.00	0.02	3.36
1892-93...	0.04	0.00	0.00	T.	T.	[0.57]	1.53	0.00	0.31	0.00	0.40	0.42	3.27
1893-94...	0.30	0.00	0.30	0.11	0.00	T.	0.74	0.00	T.	0.00	0.36	0.10	1.91
1894-95...	0.51	0.84	0.00	0.40	0.77	.....	.....	.....	.....	.....	.....	.....	.....
Mean..	0.17	0.21	0.30	0.53	0.42	0.57	0.29	0.09	0.07	.....	0.14	0.36	3.15

Miscellaneous rainfall observations in Arizona, 1896.

Stations.	Elevation.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Total.
Buttes.	1,600	0.66	0.16	0.77	0.12	0.00	0.00	3.10	0.90	1.69	1.27	0.67	1.09	10.43
Pinal ..	2,550	.....	.....	.....	0.20	0.00	0.00	2.13	1.19	0.90	3.28	1.22	1.27	.....
Whitlows.	2,050	.....	.....	.....	.....	0.00	0.06	2.67	1.58	1.68	3.16	1.21	0.91	.....
Silver King.	3,650	2.25	0.35	0.00	0.10	0.00	0.00	4.74	3.03	2.73	3.66	3.40	0.90	21.16

IRRIGATED VINEYARD NEAR PHŒNIX, ARIZONA.

WIND.

The amount and violence of the wind movement is of considerable importance in a climate such as that of Arizona, on account of its effect not only upon the vegetation but also to a certain degree upon the comfort of the inhabitants. A considerable amount of wind is not only injurious to fruit trees, but, by continually keeping the dust in motion in such an excessively dry country, renders outdoor life extremely annoying to persons who from lung or throat troubles seek refuge in an arid climate. Fortunately, as indicated by the records and shown by common experience, the wind movement in the Salt and Gila valleys is relatively small, so that the orchards are rarely injured and the amount of dust in the air is not often noticeable. With every advantage of this kind there may be a small loss, and in this case the principal drawback is in the fact that windmills can not be used to as great advantage in pumping water as out upon the Great Plains, where the wind has a sweep found nowhere else and prevails throughout the year.

Wind movements have been carefully recorded at a number of places within the Territory, the principal of these within or near the Gila Basin being Fort Apache, Fort Grant, Phœnix, Prescott, and Yuma. The record at Phœnix from 1879 to 1881 gives an average hourly wind movement of only 2.4 miles. This small amount is accounted for by the fact that the anemometer was exposed only 19 feet above the ground. As stated by the Chief of the Weather Bureau, in August, 1895, when the station was reestablished, the anemometer was placed 57 feet above the ground, giving considerable higher velocities, the monthly averages being about 5 miles per hour, or more than twice those previously obtained. The averages for Fort Apache were 6.4 miles per hour, for Fort Grant 6.8, for Prescott 6.9, and for Yuma 6.1, all of these being low in consideration of windmill efficiency.

The distribution of wind through the day is very clearly marked. Beginning at about 10 o'clock in the morning, the wind usually increases from about 3 miles per hour up to from 8 to 12 miles per hour at 3 o'clock in the afternoon. At sundown it decreases, dropping off rapidly until midnight, and slowly decreasing in force until about the middle of the forenoon of the next day. Thus, as a rule, nearly all of the effective wind movement occurs within six hours in the afternoon, or from about 1 or 2 o'clock until about sundown. The distribution of wind through the year is comparatively uniform, the greatest amount being in the spring months, the strength decreasing notably during September and October. By erecting tall windmills in well-exposed localities it may be practicable to utilize these to a notable extent in pumping water for irrigation, but to attain success these must be proportioned to the prevailing strength of the wind and to the work to be done. Even if these operate during only

one-fourth of the day, it may be possible, by providing suitable small ponds or earthen tanks, to hold sufficient water for the irrigation of gardens and a small area of forage plants.

PRODUCTS.

It need hardly be stated that on the deep alluvial soil of the valleys in such a climate as that described the growth of nearly all kinds of vegetation is luxuriant if only sufficient water be applied. All warm temperate and many semitropic products flourish here, and most of them produce in an abundance indicated by the favorable climate. The principal crops now grown are alfalfa, wheat, and barley, with more or less of peaches, grapes, apricots, oranges, and other fruits, and a variety of vegetables.

Gila Valley aspires to competition with California in the citrus fruit market, and a number of thriving orange groves indicate that in certain localities the climate and soil are favorable to success. Although there have been many failures, mainly from frost, it should be remembered that this has been the case in every citrus region at first, and that even in California only occasional spots and strips are sufficiently free from frost and other foes of the citrus family to be profitably devoted to this branch of fruit culture. Past experience seems to indicate that, as in California, there are exceptional thermal belts sufficiently exempt from frost to permit profitable growth of oranges and lemons, but such belts can be located only by observation and experience, and their discovery is often preceded by failures due to ignorance or disregard of the true conditions.

There are two respects in which Arizona seems to enjoy a decided advantage over California in the production of citrus fruits: First, the extreme heat and aridity of the climate are claimed to be unfavorable to the development and spread of such enemies of citrus growth as the scale bug (*Aspidiotus perniciosus*) in its several varieties; second, oranges, as well as some deciduous fruits, mature from two to four weeks earlier than in most parts of California, and they thus secure the advantage of an early market, which is always the best. The lemons produced in this valley are beautiful in appearance, of large size, and of excellent flavor. It would appear that this valley is under a disadvantage owing to the inconvenience or expense of curing lemons, which process requires the steady maintenance of a low temperature. The great distance from any sufficiently cool climate and the expense of maintaining local refrigeration seem to stand in the way. Claims are made that the Arizona product does not require curing as in other lemon-growing regions, but this claim seems not yet to be well established. Undoubtedly, however, though lemon culture will be somewhat more restricted than orange culture, it has come to stay. The actual location and development of favorable localities along the lines mentioned will be slow, but enough is known to guarantee the fact

FIG TREE NEAR PHŒNIX, ARIZONA.

that if citrus culture continues as profitable as it has been in the past, Arizona will some day be one of the important competitors for a share of the citrus market.

This valley appears to be preeminently the home of the grape. Table grapes of good quality and wine grapes yielding a very superior product may be grown here in abundance, as already proved by experience. Undoubtedly, also, the raisin industry will some day be important, and the hot, dry summers are favorable to the production of a superior article. In one respect, however, this valley is under a disadvantage as compared with southern California, in that it is more likely to receive sudden showers of rain during the curing season.

Claims are also made of the superiority of this region for such products as figs, prunes, almonds, pomegranates, olives, and even dates. Undoubtedly figs and prunes can be successfully grown, and the experience obtained with almonds both in this and other localities seems to justify the claims made regarding this product, but most of the other fruits mentioned are still in the experimental stages. It is doubtful if dates can be profitably grown except in some favored and well-sheltered localities. Apples appear not to do well in a climate like that of Arizona. Even those varieties which can be abundantly grown are inferior in quality and quickly decay. This fruit is better adapted to a colder climate. The same appears to be true in a less degree of pears. Most small fruits yield abundantly, and so far have been very profitable.

The quantities of fruits and vegetables which have been exported from Arizona are inconsiderable. On the contrary, large quantities of some kinds are annually imported for consumption in the industries of mining and grazing. These two interests are the main sources of exportable products, and agriculture and horticulture, so far as developed, are devoted chiefly to satisfying their wants. Alfalfa may be taken as the staple agricultural product, and is largely utilized in the fattening of cattle grown on the ranges of the adjacent mountains and foothills. Large areas of this productive forage plant are used as pasture, while others are utilized for maturing hay. Barley is largely used as hay, and also furnishes the bulk of the grain fed to live stock in the valley.

METHODS OF APPLYING WATER.

Alfalfa and the grains being the principal crops of this region, it may readily be inferred that the usual method of applying water in irrigation is by flooding the ground, since these products lend themselves to this method most readily. This system, as is well known, is also susceptible of great wastefulness in its application, especially in an ultra-arid climate, since it wets the whole surface of the ground and gives full scope to evaporation, and is often followed by baking, which favors the rise of underground waters to the surface to evaporate.

In the irrigation of fruit trees and vines the furrow method is used, which, when properly employed, is an excellent method. Pl. VII shows the ground properly prepared for the furrow method of irrigation. The water is turned into each furrow at the upper edge of the field in just sufficient quantity to run freely down the furrow without erosion, and soaks gradually away downward and sidewise. As soon as it reaches the lower end of the furrow it is shut off at the upper end; thus only a small percentage of the surface of the ground is wet, and the water reaches the roots of the trees at some distance below the surface. A light cultivator should follow irrigation, filling the furrows with loose earth and leaving the surface of the ground level

FIG. 2.—Irrigation by flooding

and dry, so that the minimum of evaporation takes place and no saturated surface is exposed to bake in the hot sun. Unfortunately, however, the predominance of the flooding system seems to influence irrigation by means of furrows, and the water is often so lavishly and carelessly applied that the ground is almost flooded, and the water stands in pools and furrows until the field becomes an absolute bog, a condition which is not only most wasteful of water, but actually injurious to the irrigated corps, by shutting off the ventilation of the roots. It also interferes with cultivation, causes the ground to bake, and allows the weeds to start. This is, however, by no means the universal practice, and many of the irrigators are approaching more and more nearly to ideal methods of irrigating. The Arizona Improve-

PALM AVENUE NEAR PHŒNIX, ARIZONA.

ment Company is setting an excellent example in this respect, as are also some of the individual irrigators, and the neat appearance of the orchards might profitably be emulated by many a city park.

WATER SUPPLY.

In comparison with the size of the Territory and the importance of its water resources, the hydrographic data are very meager. Some measurements of stream flow were made in 1889 and 1890 by the United States Irrigation Survey at a point about 14 miles above Florence, on the Gila River, known as The Buttes. Gaugings at this point were resumed in December, 1895, and are still being carried on, the

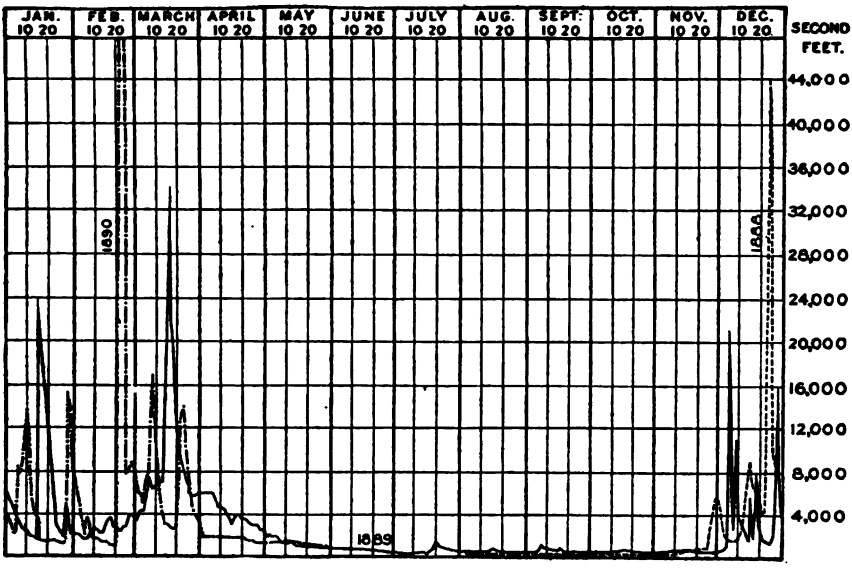


FIG. 3.—Daily discharge of Salt River at Arizona dam, 1888–1891.

results being used also to estimate the discharge from gauge readings and soundings taken during the fall of 1895 by private parties. Measurements have also been made by the United States Government of the discharge of Queen Creek, a small intermittent stream tributary to the Gila River.

Approximate estimates of the discharge of Salt River were made by Mr. Samuel Davidson from data obtained by the Arizona Cana- Cr pany at its dam a short distance below the junction of the Salt and Verde rivers.

Measurements of discharge have been more recently made on Salt and Verde rivers by the Hudson Reservoir and Canal Company. Surface velocities were measured by means of floats, and eight-tenths of the result thus obtained was assumed as the mean velocity, and mul-

tiplied into the cross section determined by sounding, to obtain the discharge, the sum of the discharges of both being adopted as the flow of Salt River below the junction. The measurements were begun on February 4, 1895, and were continued through the year without interruption except on the four days from October 4 to 7, inclusive, on Verde River, which was during that time inaccessible. An estimate for those four days has been made from the highest watermark found at the gauge and from such other data as were available. Also, for the month of January, one of the most important flood months of the year, estimates have been prepared from the daily record taken at the Arizona dam, about a mile below the junction of the two rivers. It appears from all available data that Salt River furnishes a considerably larger proportion of water than Verde River, and the assumption has been made that 60 per cent of the January flow at the Arizona dam came from Salt River above the Verde.

VIEW ON BARTLETT RANCH, NEAR PHŒNIX, ARIZONA.

The results of the computed discharges for each locality are given in the following tables:

Estimated monthly discharge of Salt River at Arizona dam, Arizona.

[Drainage area, 12,260 square miles.]

Month.	Discharge.			Total for month.	Run-off.	
	Maximum.	Minimum.	Mean.		Depth.	Per square mile.
1888.	*Second-feet.*	*Second-feet.*	*Second-feet.*	*Acre-feet.*	*Inches.*	*Second-feet.*
August	----------	----------	350	21,525	0.03	0.028
September	----------	----------	350	20,825	0.03	0.028
October	350	300	331	20,356	0.03	0.027
November	5,760	425	842	50,099	0.08	0.068
December	43,489	1,665	6,698	411,927	0.63	0.545
1889.						
January	24,953	1,665	5,947	365,740	0.56	0.48
February	3,940	1,534	2,605	144,577	0.22	0.22
March	33,794	3,563	8,745	537,817	0.82	0.71
April	5,559	2,496	3,975	236,512	0.36	0.32
May	1,784	622	1,039	63,898	0.10	0.08
June	615	356	470	27,965	0.04	0.04
July	1,311	334	495	30,522	0.05	0.04
August	755	389	417	25,645	0.04	0.03
September	1,172	389	521	31,000	0.05	0.04
October	704	319	440	27,060	0.04	0.04
November	629	532	576	34,272	0.05	0.05
December	25,371	557	5,686	349,689	0.53	0.46
1890.						
January	15,750	1,376	4,982	306,393	0.47	0.40
February	143,288	1,045	10,097	560,383	0.86	0.82
March	17,228	2,566	6,421	394,891	0.60	0.52
April	2,077	1,369	1,840	109,480	0.17	0.15
May	1,369	630	914	56,211	0.09	0.08
June	672	397	511	30,404	0.05	0.04
July	872	397	524	32,226	0.05	0.04
August	7,734	1,114	3,885	238,927	0.37	0.32
September	3,685	725	2,339	139,170	0.21	0.19
October	7,465	753	2,768	160,232	0.25	0.23
November	30,504	766	4,717	280,661	0.43	0.38
December	30,366	1,110	6,259	384,928	0.59	0.51
1891.						
January	17,127	1,060	3,416	210,084	0.32	0.28
February	300,000	825	39,201	2,175,655	3.32	3.10

Estimated discharge of Verde River above Salt River, Arizona.

[Drainage area, 6,000 square miles.]

Month.	Discharge.			Total for month.	Run-off.	
	Maximum.	Minimum.	Mean.		Depth.	Per square mile.
1895.	*Second-feet.*	*Second-feet.*	*Second-feet.*	*Acre-feet.*	*Inches.*	*Second-feet.*
January	33,000	527	4,037	248,225	0.77	0.67
February	5,800	583	1,688	93,747	0.29	0.28
March	8,400	1,887	3,720	228,734	0.71	0.62
April	2,800	280	750	44,628	0.14	0.13
May	429	127	258	15,864	0.04	0.04
June	180	129	153	9,104	0.03	0.03
July	275	116	145	8,916	0.02	0.02
August	1,426	185	359	22,074	0.07	0.06
September	348	141	176	10,473	0.03	0.03
October	3,912	197	475	29,207	0.09	0.08
November	1,800	241	463	27,550	0.09	0.08
December	881	345	391	24,042	0.08	0.07
Total, year	33,000	116	1,051	762,564	2.36	0.18
1896.						
January	354	314	324	19,923	0.06	0.05
February	352	278	154	8,852	0.03	0.03
March	338	258	276	16,971	0.06	0.05
April	237	206	220	13,090	0.04	0.04
May	206	138	172	10,576	0.03	0.03
June	137	101	117	6,962	0.02	0.02
July	3,380	98	864	53,127	0.16	0.14

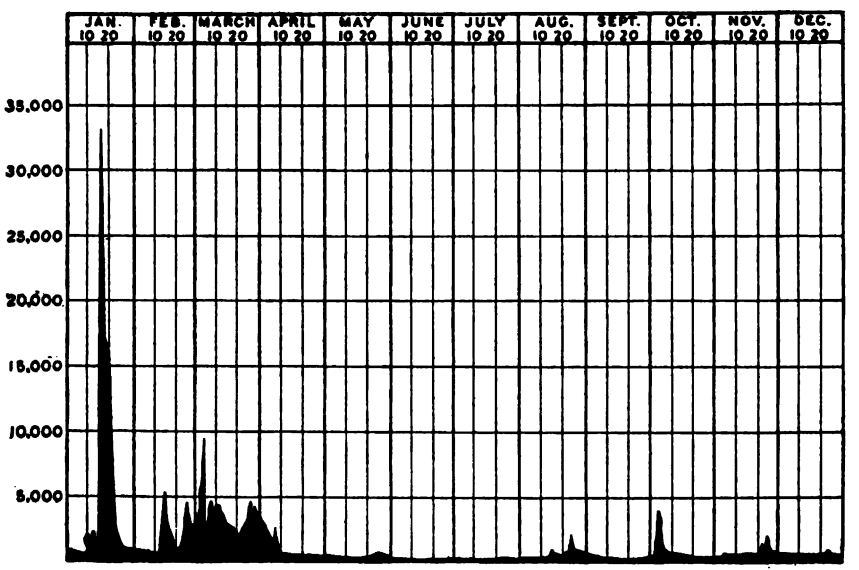


FIG. 4.—Daily discharge of Rio Verde above Salt River, 1895.

DRYING APRICOTS.

Estimated discharge of Salt River above mouth of Verde River, Arizona.

[Drainage area, 6,260 square miles.]

Month.	Discharge.			Total for month.	Run-off.	
	Maximum.	Minimum.	Mean.		Depth.	Per square mile.
1895.	*Second-feet.*	*Second-feet.*	*Second-feet.*	*Acre-feet.*	*Inches.*	*Second-feet.*
January	49,796	791	5,733	352,508	1.06	0.92
February	3,892	914	1,445	80,251	0.24	0.23
March	3,340	1,319	1,829	112,461	0.33	0.29
April	2,939	1,044	1,860	110,678	0.33	0.30
May	990	505	708	43,533	0.13	0.11
June	500	208	325	19,339	0.06	0.05
July	896	145	204	12,543	0.03	0.03
August	1,516	226	584	35,909	0.10	0.09
September	684	201	329	19,577	0.06	0.05
October	13,205	390	1,624	99,856	0.30	0.26
November	9,620	380	1,376	81,878	0.25	0.22
December	2,055	513	888	54,601	0.16	0.14
Total, year	49,796	145	1,408	1,023,134	3.05	0.22
1896.						
January	613	400	470	28,900	0.08	0.07
February	612	414	476	27,380	0.09	0.08
March	3,020	457	1,185	72,863	0.22	0.19
April	1,660	605	959	57,061	0.17	0.15
May	621	335	446	27,424	0.08	0.07
June	332	158	224	13,328	0.04	0.04
July	4,377	151	639	39,292	0.12	0.10

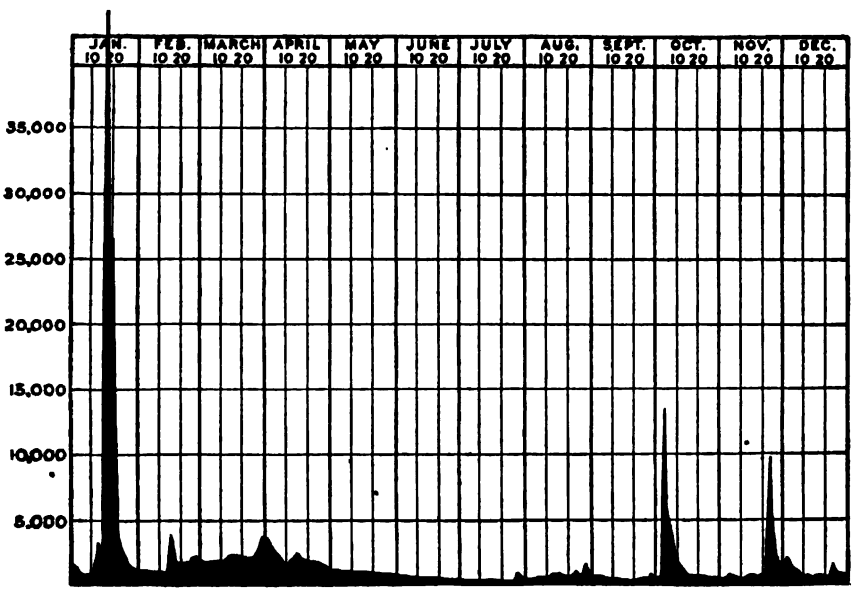


FIG. 5.—Daily discharge of Salt River above Verde, 1895.

The following table shows the discharge of Gila River for the season of 1889–90, measured by the irrigation survey, and the results from measurements still in progress for the season just closed:

Estimated discharge of Gila River at The Buttes, Arizona.

[Drainage area, 13,750 square miles.]

Month.	Discharge.			Total for month.	Run-off.	
	Maximum.	Minimum.	Mean.		Depth.	Per square mile.
1889.	*Second-feet.*	*Second-feet.*	*Second-feet.*	*Acre-feet.*	*Inches.*	*Second-feet.*
September	210	90	128	7,616	0.010	0.009
October	210	140	157	9,655	0.013	0.011
November	250	156	212	12,614	0.017	0.015
December	890	124	275	16,909	0.023	0.020
1890.						
January	2,100	310	680	41,812	0.056	0.049
February	1,514	405	578	32,100	0.043	0.042
March	710	300	387	23,795	0.032	0.028
April	333	158	238	14,161	0.019	0.017
May	150	35	87	5,350	0.007	0.006
June	35	27	28	1,666	0.002	0.002
July	3,112	11	130	7,995	0.010	0.009
August	6,330	1,115	3,137	192,888	0.263	0.228
Total, year				366,561		
1895.						
August	3,910	536	1,583	97,336	0.133	0.115
September	2,880	300	812	48,317	0.065	0.059
October	12,000	400	1,577	96,966	0.133	0.115
November	7,500	300	1,103	65,633	0.089	0.080
December	1,150	518	751	41,627	0.056	0.049
1896.						
January	560	250	396	24,349	0.032	0.028
February	340	175	209	12,022	0.016	0.015
March	356	153	242	14,880	0.021	0.018
April	340	68	180	10,710	0.014	0.013
May	68	12	32	1,968	0.002	0.002
June	32	1	5	298	0.0003	0.003
July	11,708	1	1,441	88,604	0.121	0.105
August	3,150	175	810	49,805	0.068	0.059
September	2,850	455	980	58,314	0.079	0.071
October	7,243	1,030	4,145	254,867	0.347	0.301
November	2,275	696	1,037	61,706	0.083	0.075
December	710	576	629	38,676	0.053	0.046
Total, 1896	11,708	1	842	616,201	0.839	0.062

In the above table the discharge for the period from August 1 to December 10, 1895, is estimated from observations of mean depth and width made by Mr. W. Richins, and can be considered only as a rough approximation.

IRRIGATION BY FURROW METHOD.

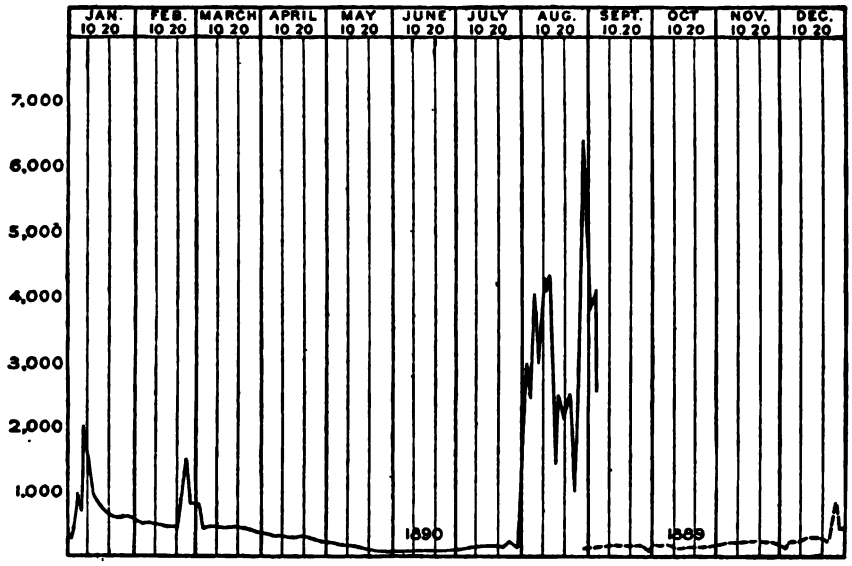


FIG. 6.—Daily discharge of Gila River at The Buttes, 1889-1890.

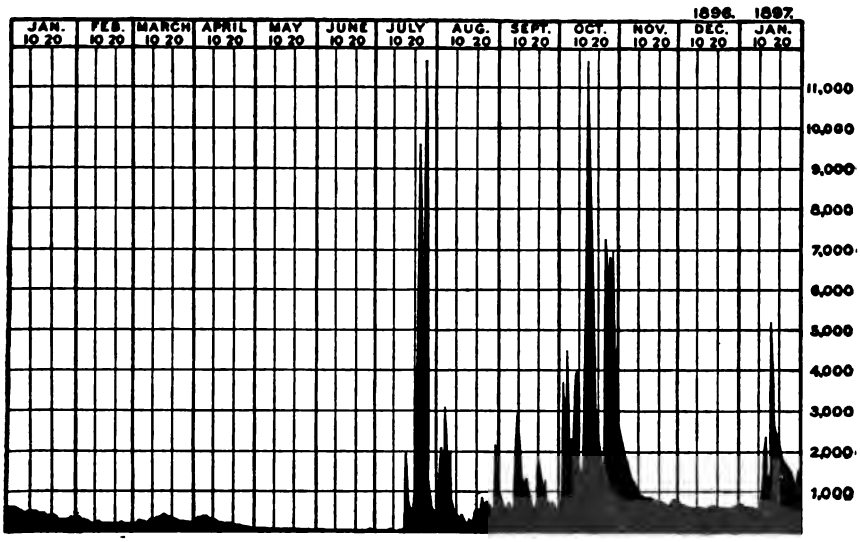


FIG. 7.—Daily discharge of Gila River at The Buttes, 1896.

Estimated monthly discharge of Queen Creek, Whitlows, Arizona.

[Drainage area, 143 square miles.]

Month.	Discharge.			Total for month.	Run-off.	
	Maximum.	Minimum.	Mean.		Depth.	Per square mile.
1896.	*Second-feet.*	*Second-feet.*	*Second-feet.*	*Acre-feet.*	*Inches.*	*Second-feet.*
January	2	2.0	2.0	123	0.016	0.014
February	2	2.0	2.0	115	0.015	0.014
March	2	2.0	2.0	123	0.016	0.014
April	2	1.0	1.5	87	0.011	0.010
May	1	1.0	1.0	61	0.008	0.007
June	1	1.0	1.0	60	0.008	0.007
July	9,000	0.0	121.6	7,480	0.980	0.850
August	1,433	0.6	13.1	805	0.106	0.092
September	3,428	0.5	17.1	1,016	0.134	0.120
October	1,188	0.5	13.3	820	0.108	0.093
November	80	0.6	1.3	80	0.010	0.009
December	207	0.6	2.0	120	0.016	0.014
Total, year	9.000	0.0	15.0	10,890	1.428	0.104

DUTY OF WATER.

The actual attained duty of water in Salt River Valley was approximately determined in the year 1895. According to figures furnished by the Arizona Improvement Company, about 60.000 acres were irri-

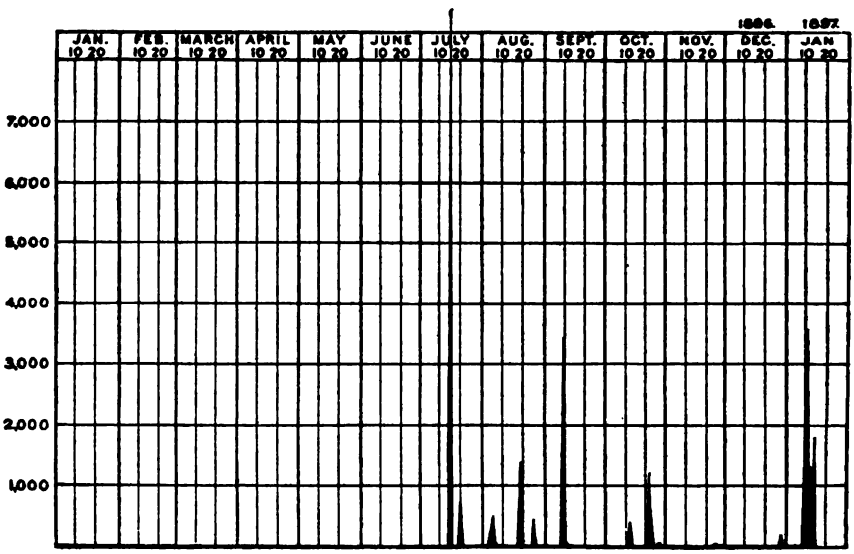


FIG. 8.—Daily discharge of Queen Creek.

gated on the north side of Salt River in that year. Of this, about 34,000 acres, or more than one-half, was in alfalfa; over one-fourth was in grain, and the remaining portion, or about one-sixth, was chiefly in fruit and garden or was occupied by streets and lots of

the city of Phœnix. The total amount of water furnished for this area is stated to have been sufficient to cover the tract an average of 4.6 feet in depth. Mr. Samuel Davidson, who has given this matter careful study, states that the average amount of water used upon an acre of alfalfa is over 5 acre-feet; the amount for grain, which is of short season, is 1½ feet in depth, while fruits require somewhat more than grain but less than alfalfa, probably an average of 3 feet in depth. As much as 11 acre-feet of water has been applied in the growing of alfalfa in this valley.

The duty of water, as indicated by past experience and present usage, can be greatly increased. During the winter and early spring, owing to melting of snow in the mountains, the river furnishes a much larger volume of water than through the rest of the year. The abundance of water at this time, together with the knowledge that it will be scarce later in the season, induces the irrigators to apply it very lavishly while they have it, and in this manner a great excess reaches the land, standing in pools and furrows for a time, and large quantities evaporating. Other quantities seep away to reappear in the bed of the river, where, after the deduction of another large proportion by evaporation, they are rediverted for irrigation by the lower canals. The amount of this seepage was measured by Mr. Cyrus C. Babb in June, 1896, and the results showed in one case an increase of over 80 second-feet in a distance of 7 miles.

Another prolific source of waste of water is the large number of long laterals required to reach the scattered tracts of irrigated land. Less than half the irrigable land below the Arizona Canal is actually cultivated, and the utilization of some of the farms requires the construction of long laterals carrying small quantities of water, from which the loss by seepage and evaporation is great. Judge Kibbey, in the opinion hereafter quoted, states that the loss of water which is carried in small ditches for the purpose of watering stock is alone sufficient for the reclamation of 10,000 acres of land, if properly applied to irrigation.

If all the irrigable lands under the canals were brought under cultivation and water supplied to them in the most economical manner practicable, irrigation carried on both night and day, and each irrigator allowed the use of a measured quantity of water for a certain number of hours, unquestionably the duty of water could be greatly increased. Probably it would ultimately be found that 2 acre-feet per year would on the average be sufficient for an acre. The great aridity of this climate will always necessitate the use of larger quantities of water than would be necessary for the same results in a more humid climate.

As shown on page 46, the Florence Canal takes from Gila River nearly 10 acre-feet of water for each acre irrigated, but this can not be considered in any sense indicative of the duty of water, as the major portion is lost by seepage and evaporation.

SILT AND ALKALI.

As indicated by its name, Salt River carries a notable quantity of mineral matter in solution. It becomes an interesting question, therefore, whether its use in irrigation will eventually lead to deterioration of the soil through the deposit of alkaline salts. Over most of the valley no such injurious effects are noticeable. This may be due partly to the excess of water applied, which, escaping to the subsoil, carries the salts in solution and bears them away through the gravels to the river bed; and accordingly it is found that where the fields are underlain at a reasonable depth by beds of gravel no accumulation of salts is noticeable, while in the vicinity of Tempe, where the subsoil is practically impervious, and where the ground water is near the surface, considerable tracts of land are to be seen impregnated with alkali, some of it to such an extent as to be of little use in its present condition except for grazing. Inquiry among the inhabitants leads to the conclusion that, although such alkaline indications were noticeable before irrigation became extensive in this valley, these areas have been greatly increased since that time, either from the rise of alkali from the subsoil or from its deposit upon the land by the irrigating waters, for which adequate drainage was not provided. Some tracts of land have even been abandoned from this cause.

It has been stated that a great excess of water is applied in this valley for irrigation and that the progress of methods of economy and the storage of surplus waters in the mountains will undoubtedly lead to a much more sparing application. The question naturally arises, therefore, whether, when the abundant leaching which is provided by the seepage downward of the excess waters is discontinued, the fields in the vicinity of Phœnix and Mesa will not become impregnated with salts to an injurious extent. Any such fear seems to be entirely unfounded. The whole valley, with the exception of the area in the vicinity of Tempe above mentioned, seems to be so thoroughly underlaid with coarse gravel that it will be entirely practicable at any time to leach out the salts by the application of a large quantity of irrigating water for that purpose. At intervals of several years, also, there occur heavy rainfalls in these valleys, which, from their sudden nature and long intervals, can not be depended upon for assistance in agriculture, but which will always be of value for leaching the soil in the manner above referred to.

MIDDLE GILA VALLEY.

There are several ditches built to divert water from the Gila River in Pinal County, but they have all been practically abandoned except the Florence Canal, on the south side, and the McClellan and Arthur ditches, on the north side of the river. This is due to the shortage of water in recent years, caused probably by increased

GILA BEND DAM, LOOKING EAST.

diversions in the upper part of the Gila Basin. The upper or Arthur is a private ditch heading just below The Buttes, without diversion works, and carries about 4 second-feet of water for a distance of about 6 miles, the loss in the sandy river bottom being great.

The McClellan ditch heads about 6 miles below the Arthur, and is a private ditch with a capacity of 14 second-feet. Water is diverted by means of a "burro" dam, which consists of a forked stick driven into the river bed, inclined slightly up stream, supporting in its forks another stick with its end driven diagonally into the sand 6 or 8 feet above. A series of these so-called "burros" are constructed across the stream and support a mass of sticks and brush, which is finally weighted down with rocks and sand. This character of dam is quite common for small ditches in the West, and of course usually requires renewal after the season of high water.

FLORENCE CANAL.

The Florence Canal heads about 3 miles below The Buttes, on the south side of the river. The water is diverted by means of an artificial shoal of rock placed diagonally across the stream. The headgate of the canal is founded upon bed rock and is constructed of wood. The grade of this canal is about 2 feet per mile. Near the head it is 45 feet in width, and was originally constructed to carry about 4 feet of water, but a shortage of water and financial difficulties have led to the neglect of the banks constructed, so that at present it is not practicable to run much more than 2 feet of water in the canal. Observations of the flow of this canal have been carried on during the year 1896, and are given in the table.

About 20 miles below the head of the canal a reservoir is constructed on the McClellan wash, as indicated on the map (Pl. XXX). This reservoir is formed by an earthen embankment or dike more than 2 miles in length, with a maximum height of about 20 feet. The area of the reservoir is in the neighborhood of 1,800 acres, and the average depth probably 6 or 7 feet. This reservoir has proved to be of great value in conserving the winter waters carried by the Florence Canal when there is an abundance in the Gila River, and also the night discharge of the canal throughout the season, to be used on the lower extension of the canal, which flows westward from the reservoir.

In the absence of any other method of conserving the winter waters such a reservoir is valuable, but as a permanent method of storing the waters of this great stream it is inefficient and wasteful. It can not receive any considerable portion of the great flood waves, as it can receive only the capacity of the Florence Canal, which feeds it. But the chief objection to this method of storage is the great area in proportion to depth which is exposed to the enormous evaporation of this climate. At least three-fourths of the capacity of this reservoir

lies within 8 feet of its surface. The annual evaporation in this climate is about 8 feet, so that at all times the loss from this source is a very large proportion of the water impounded. As a method of holding water from year to year it would be practically a failure.

The map (Pl. XXIX) shows the alignment of the Florence Canal, the location of the reservoir, and the location and extent of the irrigated lands. It will be seen that the irrigated lands are scattered, some tracts of not more than 100 acres being situated at a distance of several miles from the canal, with no other irrigated lands in the vicinity. The laterals used to convey water from the canal to these lands are wasteful of water in proportion to the amount utilized, as the amount lost through seepage and evaporation from such small, long ditches is enormous. The loss from this cause and from evaporation in the reservoir accounts abundantly for the low duty of water in this valley. As will be seen by the following table, the total discharge of the Florence Canal through the irrigating season of 1896 was about 64,444 acre-feet:

Discharge of Florence Canal, 1896.

Month.	Discharge in second-feet.			Total for month in acre-feet.
	Maximum.	Minimum.	Mean.	
March (15 days)	160	75	110	3,272
April	160	10	83	4,939
May	42	4	23	1,414
June	12	1	3	179
July	160	0	41	2,521
August	254	27	137	8,424
September	262	117	162	9,640
October	277	0	175	10,761
November	272	168	191	11,365
December	252	160	194	11,929
Total	277	0	112	64,444

The area irrigated above the reservoir was 4,457 acres, and below the reservoir 2,015 acres, making a total of 6,472 acres from which crops were matured in 1896, and these were largely of the grains. It will be seen, therefore, that nearly 10 acre-feet of water flows through the Florence Canal for each acre irrigated, being sufficient, if actually upon the land, to cover it to a depth of nearly 10 feet. The statement of areas irrigated was furnished by Mr. A. T. Colton, who was employed to measure them by the Florence Canal Company.

LOWER GILA VALLEY.

Under the term "Lower Gila Valley" may be included that portion of lowlands along Gila River beginning at the mouth of Salt River and extending to Yuma, a distance by the river, omitting minor bends, of about 170 miles. In altitude it is the lowest part of Arizona, the height

GILA BEND DAM, SPILLWAY AND HEADWORKS.

of the Southern Pacific Railroad at the town of Gila Bend being given as 737 feet, and of Yuma, at the mouth of Gila River, 40 feet. Both of these towns are considerably above the level of the bottom lands. In consequence of its low elevation the temperature is extremely high, and were it not for the aridity of the climate the summer heat would be almost unbearable. The lands along the river are of great fertility, and where watered produce abundant crops. The Southern Pacific Railroad extends in a general way parallel to the river and from 2 to 10 miles away, except above Gila Bend, where the river describes a great loop. The irrigating systems are, on the north side, the Buckeye and Monarch canals, and on the south side of the river Rumberg's ditch, Gila Bend Canal, and Upper Gila or Palmer Canal. Farther down, below Gila Bend, are a number of other systems, lying beyond the limits of the area described in this paper.

BUCKEYE CANAL.

The Buckeye Canal was begun in 1885, and water was first used in 1888. It heads on the north side of Gila River, about 4 miles below the junction of Salt River, and just below the mouth of the Agua Fria. The ownership is divided into shares, each of these representing 80 miner's inches. It is about 25 miles in length, and is built on a grade of 2 feet to the mile. At the head it is 19 feet wide, and has a depth of about 3 feet, and a capacity of about 75 cubic feet per second. It has 22 small laterals, and the main canal of course decreases in size as the laterals are taken out.

GILA BEND CANAL.

The dam of the Gila Bend Reservoir and Irrigation Company (Pl. IX) is located about 40 miles southwesterly from Phœnix and 25 miles north of the Gila Bend Station, on the Southern Pacific Railroad. It is nearly 2,400 feet long, and as originally planned was to be an overflow weir built of timbered cribs loaded with rock and anchored to piles driven in the bed of the river. After the completion of about 600 feet of the east end the expense involved induced the company to alter the plans and to build the remaining portion of loose rock, the part already constructed being intended as a waste weir, and the rock portion was built about 6 feet higher (Pl. X). The top width of the rock portion was about 18 feet, and the side slopes 1½ to 1. From the first, serious doubts of the stability of the dam were entertained by those competent to judge. It was generally conceded that the first water which overtopped the loose rock portion of the dam would wash it out. In view of this fact, and the published records of the discharge of the river showing floods approximating 300,000 cubic feet per second, it is a matter of surprise that the capacity of the waste weir was left at only about 30,000 cubic feet per second.

The first indication of a failure was in January, 1893, when a slight rise in the river caused the loose rock portion of the dam to settle

several feet. This portion was raised to its original height, and the dam was declared completed, at a cost of nearly $200,000. In March of the same year a heavy flood washed out 500 feet of the dam near the center. This breach was repaired, and in October of the same year, when the river rose again, 400 feet at the west end of the dam went out. It was now decided to make the dam a waste weir extending entirely across the river, and plans were drawn up and operations begun accordingly. The original wooden portion of the dam was thoroughly overhauled and all warped or defective timbers were taken out and replaced by new ones, and the crest of the weir was raised 2½ feet. In the portion built originally of loose rock several rows of piling were driven from 13 to 18 feet into the bed of the river. They were cut off and framed over with heavy 10-inch by 12-inch timbers. The crest of the new portion stood 2½ feet above the raised crest of the old weir. The new design also called for sheet piling above and below the dam for its entire length and a row of detached cribs below the aprons on the lower side. In January, 1895, before the new work was completed, another freshet ran about 8 feet deep over the entire length of the dam, discharging nearly 180,000 cubic feet per second, and washing out the uncompleted portion of the dam for about 400 feet from the west end, which has not been replaced. The property of this company is in litigation, and further repairs and development must await settlement of legal questions.

The canal was begun in May, 1892, and completed the following year. Its total length is 38 miles, with varying bottom widths, gradients, and depths, as shown in the following table:

Dimensions of the Gila Bend Canal.

Length.	Gradients per mile.	Bottom width.	Depth.
Miles.	*Feet.*	*Feet.*	*Feet.*
½	0.5	30	10
5½	0.5	25	10
6	0.5	24	10
6	0.5	23	10
6	0.5	22	10
7	0.6	20	10
4	0.7	15	9½
3	0.8	10	9

The side slopes were 1:1 in cut and 1½:1 in fill. The level section of the canal was a cut of 4½ feet, with embankments of 5½ feet on either side, with berms of 2½ feet. Nine flumes, aggregating 424 feet in length, were substantially built of wood. Twenty-one single and 2 double culverts, consisting of 24-inch cement pipe and aggregating 2,705 feet, were inserted. About 75 miles of laterals have been con-

GILA BEND CANAL HEADGATES.

structed. The head-gates are large iron structures between massive masonry abutments and wing walls. (See Pl. XI.) The head-gate and canal may be taken as one of the best and most substantial works of the kind yet constructed. The entire project is reported to have cost about $1,000,000.

About 10 miles below the Gila Bend Reservoir and Irrigation Company's dam the lower Gila Bend Canal heads, on the same side of the river, and covers a narrow strip of land about 15 miles in length. It is 11 feet wide, and is said to have cost about $25,000. It was first used in 1885. Water is diverted by means of a temporary dam of brush and stone, which is renewed when required. It is a cooperative concern, owned by the irrigators in the form of 36 shares, each entitling the holder to a proportionate part of the water.

SALT RIVER VALLEY.

As previously defined, Salt River Valley is taken as including the lands adjacent to Salt River extending from the mouth of its principal tributary, the Verde, down to the point where Salt River empties into Gila River, a distance in a direct line of about 40 miles. The fall of the river between these points is so great that water can be readily diverted at almost any part of the river's course and carried diagonally away from the stream, covering in the course of a few miles a considerable extent of country. As shown by the map (Pl. XXX), canals have been constructed heading at short intervals from near the upper end of the valley down along its whole course. The principal of these canals are shown in the following list, which gives also the approximate length and the year when first used. These canals have an aggregate of nearly 600 miles of lateral ditches.

Principal canals of Salt River Valley.

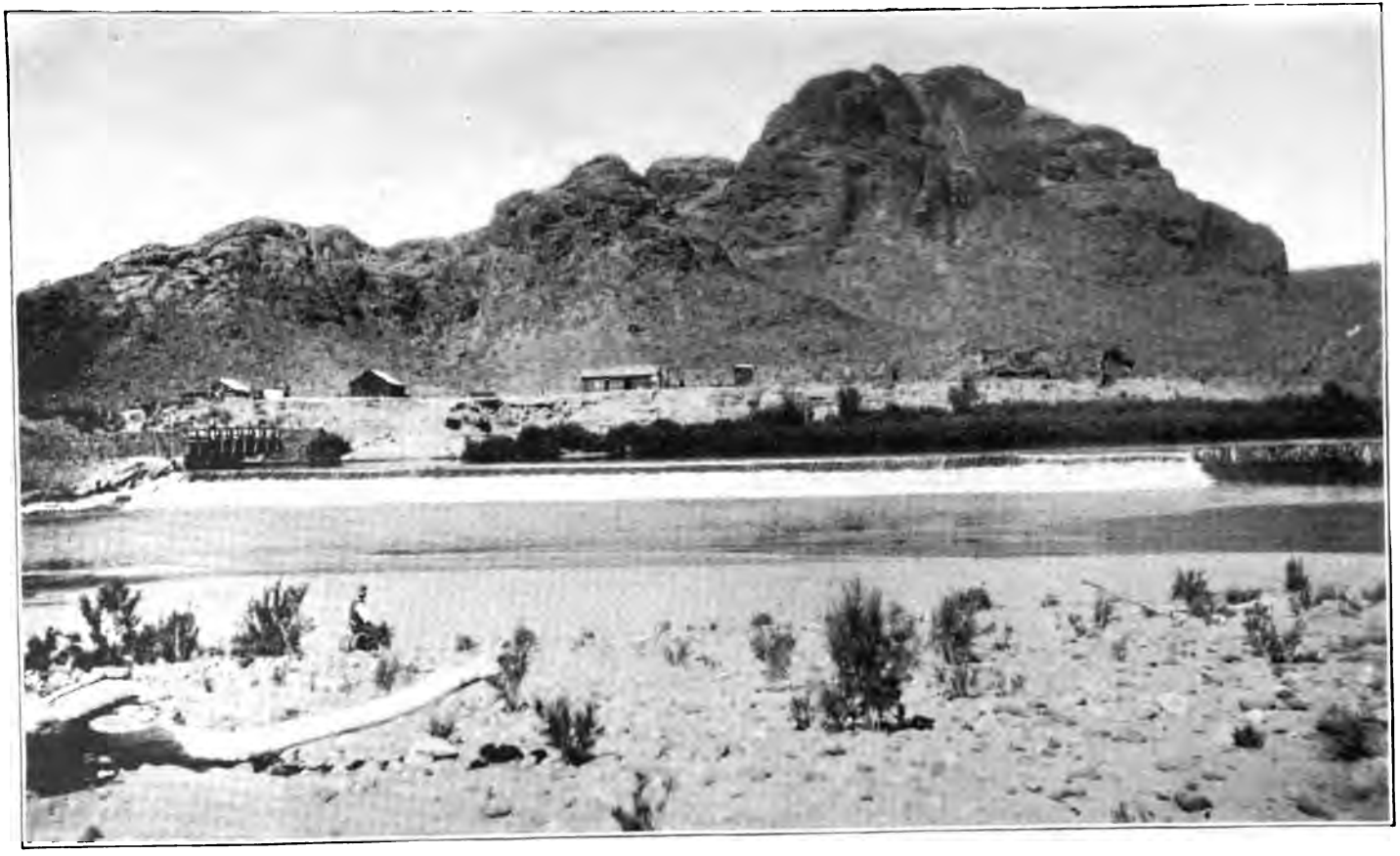
Name.	Length.	When first used.
	Miles.	
NORTH SIDE.		
Arizona	47	1885
Grand	27	1878
Maricopa	26	1868
Salt River Valley	19	1868
Farmers'	5	.....
St. Johns	12	.....
SOUTH SIDE.		
Highland	22	1889
Consolidated	40	1894
Old Mesa	10	1878
Utah	20	1877
Tempe	30	1871
San Francisco	6	1871

The following description gives the principal facts obtainable concerning these canals, the descriptions being arranged in geographic order, first those on the north side and then those on the south.

ARIZONA AND OTHER NORTH-SIDE CANALS.

The Arizona Canal, constructed in the years 1883 and 1884, heads highest on the river and has the only permanent dam. This dam, or weir, is located about 1 mile below the mouth of the Verde, and extends diagonally across the river in a northeasterly direction from a rock projecting into the stream from the right bank to a rock on the left bank. At the time of its construction the river channel was against the right bank, and on the left side a gravel bar sloping from the channel to the bank extended to a depth of 8 or 10 feet. This bar was excavated to the surface of low water for a width of 60 feet, and the dam was begun with mudsills 8 inches by 10 inches by 48 feet, laid parallel with the stream at intervals of 10 feet. Upon the upstream half of these sills is built a continuous crib with cross-ties every 10 feet, into which the rails are gained, a space of 4 inches being left between the rails, which are fastened with 12-inch drift bolts three-fourths inch in diameter. The front and back sides of the crib have a batter of one-fourth to one, and are covered with 2-inch plank with 6-inch sheet piling drifting at its back. The rail is laid lengthwise on mudsills in the center of the crib, and constitutes the only floor of the crib, which is filled with bowlders.

The crest of the dam for a distance of 416 feet on the left bank is 10 feet above low water and is covered with 3-inch plank, spiked to the rails and braced and propped from cross-ties below, and having a slope of 3 feet upstream. Rails are laid upon the mudsills projecting 24 feet downstream, 4 feet apart, and covered with 3-inch plank for apron, and sheet piling 3 inches thick and 18 feet in length driven at lower edge of apron. Below the apron the gravel was excavated and cribs put in 4 feet deep and 12 feet wide, of various lengths from 10 to 24 feet, with double rods to bind corners. These cribs were filled with rock and covered with 3-inch plank. The portion of the dam just described is still standing. The part built across the channel was constructed similarly, and went out in the great flood of 1891 and was replaced by a more substantial structure, having the overfall broken into a series of steps, and the 5-foot sections of dam bound together with 1¼-inch iron rods from top to bottom. Sheet piling was driven at both the heel and toe of the renewed portion. The current strikes the crest of the dam at an angle of about 12°. Between the southwest end of the dam and the canal head-gates a wasteway was blasted out of the rock 36 feet in length, and prepared to receive slash boards, which can be easily removed when necessary to draw off the water from the back of the dam during low water for repairs. The total distance at high water over the dam wasteway and rock on level with dam is 1,000 feet.



VIEW OF ORIGINAL ARIZONA DAM.

GREAT FLOOD OF 1890 ON SALT RIVER.

The head works of the canal are in solid rock, with masonry abutments and wing walls and wooden gates. The bottom width of the canal is 36 feet at the head, and becomes narrower toward the lower end. The estimated capacity is 1,000 cubic feet per second. For the first 3 or 4 miles there is considerable heavy construction, the country being somewhat rough, and the material to be moved consisting largely of gravel, with some solid rock. The canal was first used in 1885. It is 47 miles long, and cost $600,000.

Grand Canal, heading about 2½ miles above the consolidated head of the Salt River Valley and Maricopa canals, was constructed in 1878. The capacity of this canal is 215 second-feet. It has been absorbed by the Arizona Canal Company, its head works have been abandoned, and it receives water from the Arizona Canal through what is called the Crosscut Canal. This latter was constructed in 1889, partly for the purpose of economizing the water to which the Grand Canal is entitled by carrying it through the Arizona Canal instead of through the sandy bed of the river, and partly to utilize for power purposes the fall between the Arizona and Grand canals. Its capacity is about 375 second-feet, and it supplies water for the Grand Canal, and at times during low water for the Salt River Valley and Maricopa canals.

The oldest diversion from Salt River for irrigation purposes is the Salt River Valley Canal, constructed in 1867 by Jack Swilling and his associates, and called originally the Swilling Ditch. It is on the north side of the river, about 5 miles east of Phœnix. Some time after its construction another canal or branch was taken from it, at a point about 3 miles below its head, which became known as the Maricopa Canal. These two canals with a common head are sometimes called the Consolidated Canals. The diversion is by means of an artificial shoal formed of rocks and brush through wooden head-gates, with solid masonry abutments and wing walls. The capacity of Salt River Valley and Maricopa canals jointly is about 275 second-feet. Both canals are now controlled by the Arizona Canal Company.

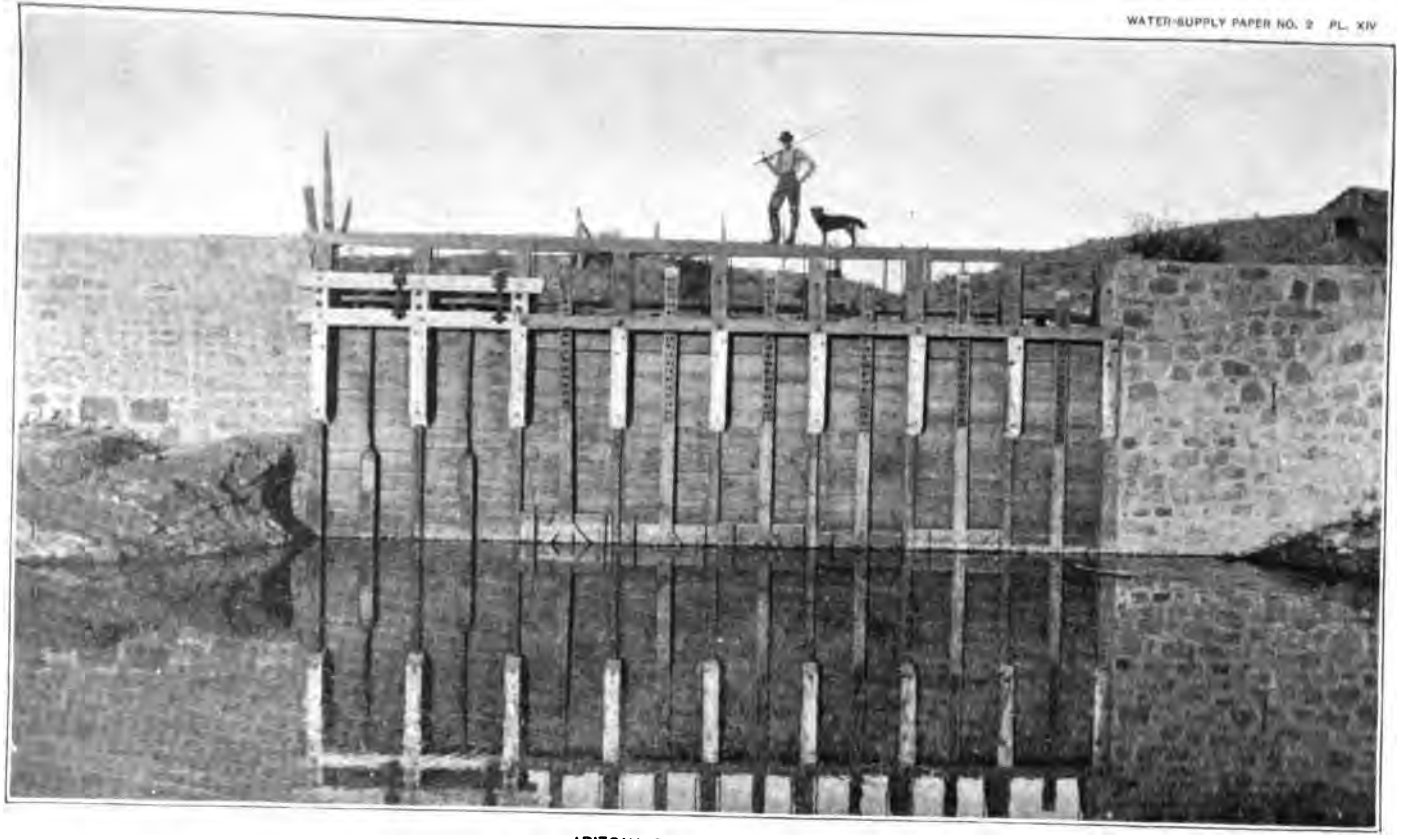
SOUTH-SIDE CANALS.

The Highland Canal was built early in 1889. It takes water on the south side of the river, about 2 miles below the head of the Arizona Canal, and has a capacity of about 100 cubic feet per second.

The Mesa City Canal was begun in 1879 by the Mesa Canal Company, a corporation composed of the owners of the land to be watered by the canal. It emerges from the river on the south side, about 2½ miles above the head of the Utah Canal, being above the head of all the canals and ditches previously constructed. It supplies water to Mesa City and adjoining country, and has a capacity of about 175 second-feet. Its alignment for a considerable distance is said to have followed the line of one of the prehistoric canals of this valley. One share of stock in this canal represents a maximum of 17½ miner's

inches, or a little over two-fifths of a cubic foot per second. The water represented by a share supplies about 40 acres of land and is valued at present at about $250. The annual charge per share is $14. Considerable expense and annoyance was experienced for many years from the insecure head works of this canal, the farmers frequently being obliged to quit work in the busy season to restore their supply of irrigating water. Finally, in 1893, the Consolidated Canal Company was formed, which entered into a contract to build new head works and to deliver a specific quantity of water for a consideration at a designated point on the Mesa Canal for the use of the owners of that canal. This company built a shoal of large bowlders across the river, which withstands the floods of the river, but it gradually settled, at first into the sand and gravel of the river bed. As settlement proceeded it has been built up and constitutes a very fair means of diversion. At the south end of this shoal are built massive granite masonry abutments and wing walls, between which the canal flows through wooden gates directly into the mesa of bowlders and hardpan, through which it is constructed in a deep cut for a distance of over 2 miles, the maximum cut being about 26 feet. This heavy construction was performed by a huge dredge with a dipper capacity of 2 cubic yards of earth and having a lift of 26 feet. At the end of these 2 miles the Consolidated Canal follows for some distance the alignment of the Mesa Canal until it reaches a point about 3 miles northeast of Mesa City, which is designated as the point of delivery of the specific quantity of water for the irrigators under the Mesa Canal. At this point the water for the Mesa Canal Company is discharged into their old canal, and two branches are constructed by the Consolidated Canal Company, one starting southeast for irrigating purposes, and one running due west for about 2 miles until it reaches the edge of the mesa, just above the Tempe Canal, where a large power plant is constructed for electric lighting and power purposes, using the irrigating water to which the Tempe Canal is entitled and discharging it from the wheels into the Tempe Canal about 1½ miles below its head. For some time the right to use the irrigating waters of the Tempe Canal was questioned, but this matter is now said to be adjusted. The eastern branch of the Consolidated Canal above mentioned is constructed on a light-grade line, in a general southerly direction, to the boundary of the Gila River Indian Reservation. By carrying the water of the Tempe Canal through the Consolidated Canal instead of through the sandy river bed, a considerable loss by evaporation is prevented, and the water available for irrigation is thereby increased. In this manner the Consolidated Canal obtains a right to some irrigation waters.

The Utah Canal was constructed in 1877 on the south side of the river, heading about 5 miles above the head of the Tempe Canal. It was constructed and is operated by the owners and occupants of the



ARIZONA CANAL HEADGATES.

VIEW OF PRESENT ARIZONA DAM.

lands which are irrigated by its waters, and the association is unincorporated, the water rights being represented by certificates which are transferable. Its capacity is about 175 second-feet.

In 1870 a ditch was constructed on the south side of the river, known as the Tempe Irrigating Canal. It heads about 7 miles above the Salt River Valley Canal, and was carrying in June, 1896, about 114 cubic feet of water per second. This is a community ditch, the property of the owners of the land irrigated from it, the shareholders being unincorporated. The canal has a carrying capacity of 337 cubic feet of water per second.

The San Francisco Canal, known also as the Wormser Canal, was constructed on the south side of the river in 1875. It heads a short distance below the town of Tempe, and has a capacity of about 52 second-feet.

Mr. C. T. Hayden, a shareholder of the Tempe Canal Company, in the year 1874 erected a flouring mill at Tempe, and by an arrangement with the other shareholders obtained a supply of 27½ cubic feet of water per second to run his mill.

AREA IRRIGATED.

It is extremely difficult to obtain reliable figures concerning the area irrigated in any locality. This is true in the Salt River Valley as elsewhere, and is due not only to the fact that farmers as a rule do not keep records of the results of their labors, but also because of the many influences tending toward exaggeration of statements. It is usually to the interest of the farmer as well as the canal owner to claim that a large area is irrigated, so that in case of subsequent controversies over water rights his title to the use of water may be supported. The matter of definition also, as to what may be considered as irrigated, introduces complications. In order to secure title under the desert act, claims are made and proofs submitted that hundreds of acres are irrigated, although as a matter of fact this irrigation is of the most nominal character, and to the eye the land has received no apparent benefit.

A systematic attempt was made by the Eleventh Census to obtain an exact statement as to the amount of land actually irrigated and cropped in the census year 1889. A farm-to-farm enumeration was made for the purpose of obtaining the area of land in each farm, the amount improved, cultivated, and irrigated, the area and quantity of crops, and many other details. It was found during this census that claims were frequently made that 160 acres were irrigated, when the crops aggregated only about 30 or 40 acres. Examination revealed that as a rule the amount claimed as irrigated represented the amount of land under ditch and to which water might perhaps be taken, while actually, either from deficiency of water or other cause, successful irrigation was conducted only upon the smaller area.

The total area irrigated in Arizona and from which crops were obtained during the season of 1889, according to the Eleventh Census, was only 65,821 acres, the greater part of this being in barley, alfalfa, and other forage crops. Of this amount, the area irrigated in Maricopa County was found to be 35,212 acres. A large portion of this was on the south side of Salt River. For comparison, and to illustrate the difference obtained by estimates based upon the claims of canal owners and farmers, it is stated that on the north side of Salt River, in Maricopa County, there were irrigated in 1889, under the Arizona Canal, 56,000 acres. This amount, or 350 quarter sections, is the quantity given in the decision noted later on page 61. The area given as irrigated from the Arizona Canal system in 1895 was about 60,000 acres. The discrepancy between the census figures and the amount adjudicated may be due to a number of causes, but is probably accounted for largely by the fact that many of the tracts to which water rights were adjudicated were cultivated only in part, and did not yield crops of sufficient size to be reported by the owners or enumerators. Many of the tracts formerly claimed as irrigated have since the acquisition of title been left uncultivated. It is suggestive to note in this connection that the adjudicated rights of some of the older canals aggregate more than their entire capacity.

The first irrigation under the Arizona Canal occurred in 1885. The decision handed down by Judge Kibbey (page 61) adjudicated rights for the year 1884 aggregating 82,600 acres. On the basis of the duty of water assumed by the court—100 acres per second-foot—it would require for the satisfaction of these rights a flow of 826 cubic feet per second. By reference to the table of discharges of Salt River at Arizona dam, on page 37, it is seen that the mean flow for the month of July in 1889 was 495 second-feet, and for the same month in 1890 it was 524 second-feet. The flow for the month of June, which it would be safe to assume as available for irrigation, would be not more than 500 cubic feet per second, whereas in the year 1884, as just shown, before the Arizona Canal was brought into use, 826 second-feet were required to satisfy the legal rights existing in the valley. But crops of grain can be matured in this valley by the growth in the winter and spring, and large areas are undoubtedly matured every year before the 1st of June. The minimum flow for the month of May, however, is given as 622 second-feet in 1889, and as 630 second-feet in 1890, while the mean for the entire month in 1890 is 914 second-feet.

The two minima given would seem to indicate that a shortage was imminent even in the month of May in 1884, if the rights as adjudicated were all claimed. If this was the case in 1884, what can be said of 1889, when instead of 82,600 acres claiming water there have been adjudicated rights amounting to 151,360 acres? The areas that have been irrigated since 1889 under the Arizona Canal system have probably been increased, so that the total area using or claiming water

FALLS ON ARIZONA CANAL.

VIEW ON CROSSCUT CANAL.

from Salt River is double what it was in 1884, and consequently more than double the capacity of the river to supply in ordinary years, and still more beyond its capacity in dry years. But the condition of irrigation in Salt River Valley is not as bad as these figures would seem to imply. As above indicated, the adjudicated rights are probably greater than the areas actually irrigated in the years given, and cultivation has been discontinued on some of the tracts formerly irrigated. There is considerable competition for water among irrigators during the dry months, and this has been one cause of the abandonment of areas formerly cultivated.

ADJUDICATION OF WATER RIGHTS.

It will readily be seen by the foregoing that the various canals and ditches taking water from Salt River have an aggregate capacity much larger than the low-water flow of the river, which is in the neighborhood of 300 cubic feet per second, and the irrigable land under these canals is proportionately in excess of the water supply in the dry season.

These facts led to the institution of a suit before Judge Joseph H. Kibbey to determine the rights of the various proprietors, the trial of which was begun in March, 1890, and concluded in August of that year. The amount of evidence taken in the case is very voluminous, consisting of 6,000 pages of typewritten matter. The argument of the case was heard in February, 1891, and occupied fifteen days. Many interesting principles of the law relating to water rights were enunciated in this decision, relating to the method of acquiring water rights and the rights of the community concerning the reasonable use as opposed to the waste of water. This decision was published, but the pamphlet is now out of print, and a portion of the decision is here reprinted on account of its value and interest in connection with this subject.

JUDGE KIBBEY'S DECISION.

In 1848, and from that time until 1863, that part of the Territory of Arizona within which is the Salt River Valley was a part of the Territory of New Mexico, and there were expressly enacted by that Territory laws governing the appropriation and use of water for irrigation. In 1863 part of the then Territory of New Mexico was erected into a temporary government by the name of the Territory of Arizona, and the laws of New Mexico were, by the acts of Congress establishing the Territory of Arizona, made applicable to that Territory.

In 1864 the First legislative assembly of the Territory convened and enacted the code of laws commonly known and cited as the Howell Code. By article 22 of an act of that legislature, known and designated as the "Bill of Rights," it was provided that "all streams, lakes, and ponds of water capable of being used for the purposes of navigation or irrigation are hereby declared to be public property, and no individual or corporation shall have the right to appropriate them exclusively to their own private use, except under such equitable regulations and restrictions as the legislature shall provide for that purpose." This act went into force on the 1st day of January, 1865. This provision has been incorporated in

the successive revisions of our code, and is still a part of our statutory law. At the same session of the legislature, and by a law taking effect at the same time, an act governing acequias and irrigating canals was adopted.

Section 1 of that act provides that "all rivers, creeks, and streams of running water in the Territory of Arizona are hereby declared to be public and applicable to purposes of irrigation and mining," as afterwards provided.

Section 2 saves all vested rights.

Section 3 provides that "all the inhabitants of this Territory who own or possess arable or irrigable lands shall have the right to construct public or private acequias and obtain the necessary water for the same from any convenient river, creek, or stream of running water."

Section 4 provides for the assessment of damages resulting from the construction of ditches across private property of individuals.

Section 5 provides that no inhabitant of this Territory shall have the right to erect any dam, or build a mill, or place any machinery, or open any sluice, or make any dike, except such as are used for mining purposes or the reduction of metals, as provided for in sections 6 and 7 in the act, that may impede or obstruct the irrigation of any lands or fields, as the right to irrigate the fields and arable lands shall be preferable to all others, and the justices of the peace of their respective precincts shall hear and determine the question relative to all such obstructions in a summary manner and cause the removal of the same by order directed to a constable of the precinct or sheriff of the county, who shall proceed to execute the same without delay.

Section 7 directs that when any ditch or acequia shall be taken out for agricultural purposes the person or persons so taking out such ditch or acequia shall have the exclusive right to the water, or so much thereof as shall be necessary for the said purposes, and if at any time the water so required shall be taken for mining operations the person or persons owning said water shall be entitled to damages, to be assessed in the manner provided in section 6.

Section 8 prohibits the construction or maintenance of bypaths and footpaths across cultivated fields.

Section 9 provides that all owners and proprietors of arable and irrigable lands bordering on, or irrigable by, any public acequia shall labor on such public acequia, whether such owners or proprietors cultivate the land or not.

Section 10 provides that persons interested in a public acequia, whether owners or lessees of land, shall labor thereon in proportion to the amount of land owned or held by them which may be irrigated by the ditch.

Section 11 provides that animals shall be herded to prevent trespass upon cultivated fields.

Section 12 provides that in case a community desire to construct an acequia and the persons desiring to construct the same are the owners or proprietors of the land upon which they design to construct the acequia, no one shall be bound to pay damages for the land taken.

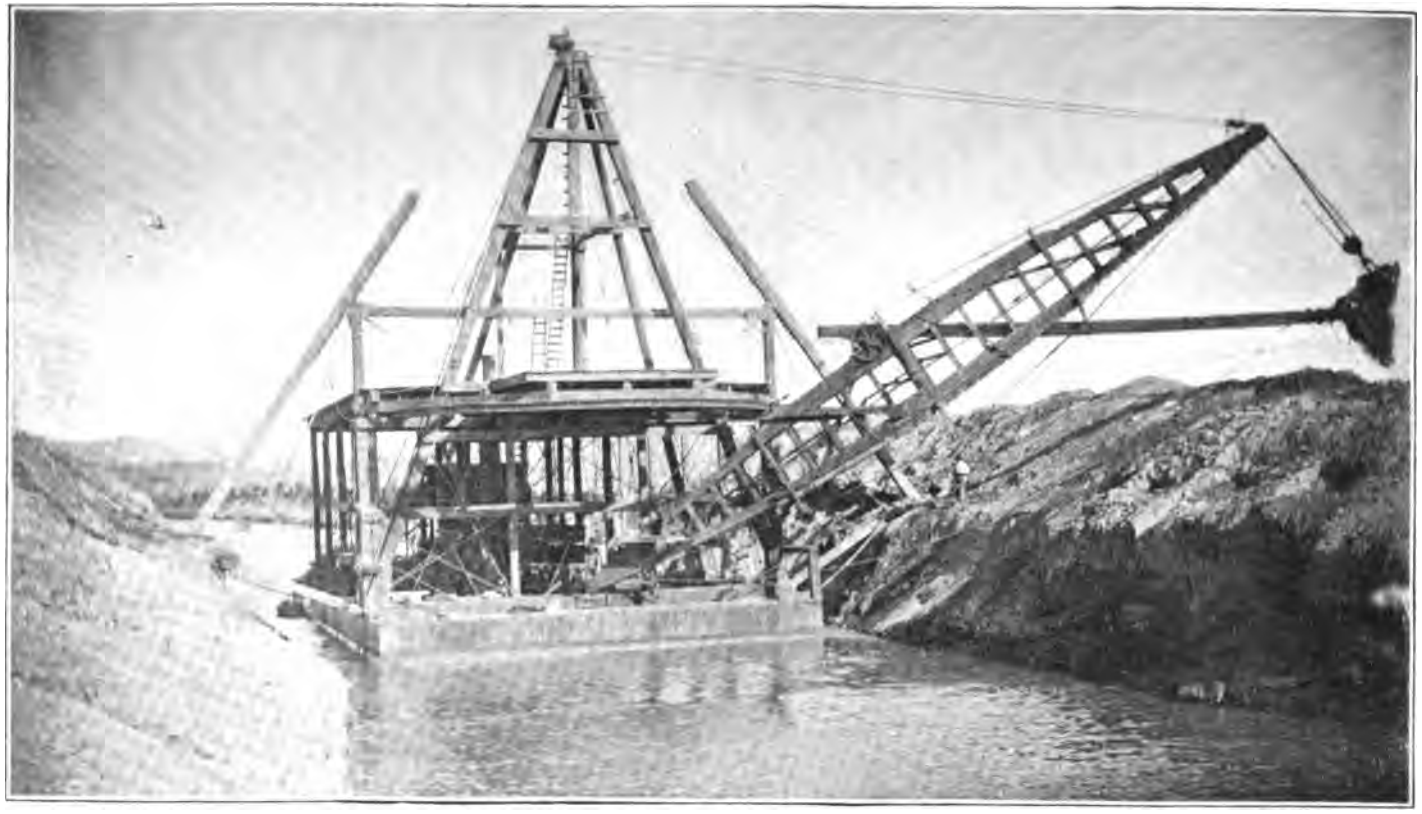
Section 13 provides for the election of overseers of public acequias.

Section 14 prescribes the manner of the election of overseers.

Section 15 provides for payment for services of the overseers.

Section 16 prescribes the duty of the overseers, of which, among others, is enumerated the duty to distribute and apportion the water in proportion to the quantity to which each one is entitled according to the land cultivated by him, and that in making such apportionment he shall take into consideration the nature of the seed sown or planted and the crops and the plants cultivated.

Section 17 provides that "during years when a scarcity of water shall exist owners of fields shall have precedence of the water for irrigation according to the dates of their respective titles or their occupation of their lands either by themselves or their grantors. The oldest titles shall have precedence always."



MAMMOTH DREDGE EXCAVATING MESA CONSOLIDATED CANAL.

Section 18 provides for the contribution of labors by irrigators to the maintenance of the acequia.

Section 19 prescribes penalties for malfeasance or nonfeasance of the overseer in discharging his duties, and provides for his removal in certain events.

Section 20 provides for the filling of the vacancy occasioned by the removal of the overseer.

Section 21 imposes a penalty upon the owner or proprietor of land irrigated by an acequia for neglect or refusal to furnish the number of laborers required by the overseer for the maintenance and repair of the acequia.

Section 22 prescribes the penalties against any person who shall in any manner interfere with, impede, or obstruct any such acequia or use the water from it without the consent of the overseer.

Section 23 provides that the fines and forfeitures recovered under the provisions of the act shall be applied by the overseers to the improvement, excavation, and repair of the acequia, and for the construction of bridges at points where they may be crossed by public streets or roads.

Section 24 provides for the appeal from judgment of conviction under any of the provisions of the act.

Section 25. "The regulation of acequias which have been worked according to the laws and customs of Sonora and the usages of the people of Arizona shall remain as they were made and used up to this day, and the provisions of this chapter shall be enforced and observed from the day of its publication."

Section 26 provides that plants and trees growing on the banks of any acequias shall belong to the owners of the land through which the acequia runs.

Section 27 provides that any person owning lands which may include a spring or stream of running water, or owning lands upon a river where there is not population sufficient to form a public acequia, may construct a private acequia for his own uses, subject to his own regulations, provided he does not interfere with the rights of others.

In the year 1866 the National Congress enacted a law for the disposal of its lands containing valuable minerals, and among the provisions of that act, with some subsequent slight verbal changes not affecting the substance or meaning, is the following (sec. 2339, Revised Statutes of the United States):

"Whenever by priority of possession rights to the use of water for mineral, for mining, agricultural, manufacturing, or other purposes, have vested and accrued, and the same are recognized and acknowledged by the local customs, laws, and decisions of courts, the possessors and owners of such vested rights shall be maintained and protected in the same, and the right of way for the construction of ditches and canals for the purposes herein specified is acknowledged and confirmed; but whenever any person, in the construction of a ditch or canal, injures or damages the possession of any settler upon the public land, the party committing such injury or damage shall be liable to the party injured for such injury or damage."

Section 2340 provides "that all patents granted, or preemption or homestead allowed, shall be subject to any vested or accrued water rights, or rights to ditches or reservoir used in connection with such water rights, as may have been acquired under or recognized by the preceding section."

This provision of the act of Congress has been held by the Supreme Court of the United States, and of some of the States, not only to confirm rights that have been initiated or had vested prior to the passage of the act, but that it was continuous in its operation and was the license of the Government to persons to hereafter appropriate water on the public domain for agricultural, mining, manufacturing, or other purposes. (98 U. S., 453; 13 Oregon, 596.)

On the 3d of March, 1877, there went into effect an act of Congress providing that any citizen of the United States, or any who had declared his intention to

become such, upon the payment of 25 cents per acre, may file a declaration, with the register and receiver of the land district in which any desert land is situated, of his intent to reclaim a tract of land not exceeding one section, by conducting water thereon within the period of three years thereafter. It provides that the right to the use of the water by the person so conducting the same on or to any tract of desert land of 640 acres "shall depend upon bona fide prior appropriation, and such rights shall not exceed the amount of water actually appropriated and necessarily used for the purposes of irrigation and reclamation, and all surplus water over and above such actual appropriation and use, together with the water of all lakes, rivers, and other sources of water supply upon the public lands and not navigable, shall remain and be held free for the appropriation and use of the public for irrigation, mining, and manufacturing purposes, subject to existing rights."

By an act of the legislative assembly of the Territory of Arizona approved February 19, 1877, all the laws of the Territory then in force were directed to be recompiled, which was done; and the compilation is known and cited as the "Compiled laws of 1877," among which are the Bill of Rights and the various provisions governing the construction of private and public acequias and the appropriation and use of water for irrigation that we have above quoted from the Howell Code. The same laws have been carried forward into the revision of 1887. In 1887 the acequia law was not reenacted, but not having been repealed, it is still in force, and the editors of the revision of 1887 have incorporated it in that revision. (Sects. 3199–3226, R. S., 1887, Arizona.)

In 1887 the legislative assembly enacted a law providing that the common-law doctrine of riparian rights shall not obtain or be of any force or effect in this Territory. (Sec. 3198, R. S., 1887. Arizona.)

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REASONABLE USE OF WATER.

Incident to the right of the inhabitants of this Territory to appropriate water for irrigation or other uses is the restriction that the means of diversion shall be reasonably adapted to the purpose, to the end that the water that is made free to the public shall not be diminished beyond the quantity sufficient to supply the actual needs of the appropriator; that the means of application of the water to the purposes for which it is appropriated shall be of a character to insure as small a consumption of water as is reasonably consistent to the accomplishment of that purpose. No man has a right to waste a drop of water. Any excess of water that he diverts and wastes by carelessness, negligence, or ignorance of economic methods of cultivation or irrigation, or failure to adopt them, he unlawfully diverts.

It appears from the evidence in this case that large quantities of water are allowed to flow in the various canals and ditches to supply stock with water. This necessarily involves a great waste of water. At a small estimate, I should think the evidence discloses an amount of water wasted thus sufficient, if properly applied to irrigation, to make productive 10,000 acres of land. The amount of water actually consumed by the stock is insignificant. The loss is that due to evaporation and seepage in its long passage through the various canals and the miles of subsidiary ditches. This seems to me to be an unreasonable use of water. I do not mean to deny the right to the use of water for stock, for it has always been a recognized use, like that for domestic purposes. But it can not, I think, be diverted from its original course for that purpose. It has always been the law that stock and the public could drink from a water course, but not to impede its flow or diminish its quantity for that purpose. Instead, I consider the law to be, of bringing the water diverted from a natural water course a long distance by means necessarily involving an enormous proportionate waste to water stock, the stock must be taken to the natural water course to drink, or otherwise provided for.

DIVISION BOX ON TEMPE CANAL.

If the water be in the ditches on a man's ranch in the course of application directly to irrigation, it might be permitted to allow stock to drink of it; but it is an unreasonable use of it to permit water to be in the ditches for that purpose alone.

Another matter for our consideration in this connection is the right of the appropriator of water to the exclusive possession, maintenance, operation, and the use of the conduit, as he has prepared it, for the diversion of the water, whether or not, having constructed such a conduit, he thereby has the right to have the water flow in the river to that conduit and thence to the point where he desires to use it, or whether his right is limited to the actual delivery of water to his lands, with or without increased expense to himself, whether it be by means therefor provided by himself or by means provided by some one else. To illustrate: If those who operate the Highland Canal should divert from the river the water to which the consumers under the Tempe, the Mesa, the Utah, and the San Francisco are entitled, and yet should that company deliver the water so diverted through its own canal to and upon the lands of those under the other canals named, in the quantities to which they are entitled, would those who constructed and since have operated and maintained the Tempe Canal, the Utah Canal, the Mesa Canal, and the San Francisco Canal have any just cause for complaint, or have the owners of those mentioned canals a vested right not only to the use of the water for the purpose of irrigation, but also to have it conveyed by means of its own conduit?

Following out to their sequence the propositions I have advanced as to the ownership of water and the right of appropriation, I am of the opinion that the entire right of the appropriator for irrigation is limited to the delivery of water sufficient for the purpose upon his land at a point where he can use it for irrigation, and that so long as such water is so delivered he may be indifferent to any acts of diversion or obstruction of the flow of water in the natural water course, and has no just cause for complaint therefor. He might be compelled to adopt a more expensive means of delivery of the water to his lands if the means that he has already adopted are such as would result in the loss of water; for, as we have repeatedly affirmed, the water is public property; it is a common stock to which all may go, and no man has any right by faulty construction of his conduits, or by their deficient construction, or by a desire to appropriate more than his share of the water, to diminish that common stock of the water to any greater extent than his necessities require.

This brings us to the question whether or not it is the duty of the prior appropriator to make use of such new means as may result in the more economical conveyance of water than those which he had heretofore provided for himself. Whether or not it would be his duty, if, for instance, he was an irrigator under the Tempe Canal, to construct a new conduit from the Highland Canal to his lands, and thereby conduct his water at a considerable saving of the common stock of water, assuming, of course, that the Highland Canal is capable of carrying, in addition to that which it is already under obligation to carry, the quantity sufficient for his use.

The variety of means adopted for the diversion of water vary under different conditions. The person who first appropriates usually finds in the natural water course a volume of water in excess of that which he himself needs, and to divert the comparatively small proportion of the whole volume which he may need would be inexpensive and easy of accomplishment. It is usually unnecessary for the first appropriator to construct a dam, or that he should excavate a ditch to the bottom of the water course whence he divert his water; because of the superabundance in the natural water course enough for his purpose may be diverted by less expensive means. As, however, others seek, subsequently, to appropriate a

portion of the same stream above the point of diversion by the first, a diminution of the quantity of the water going down to the first appropriator results in such a reduction of the volume of water that the means adopted by the first appropriator will not enable him to continue his diversion, and he must, in order to get the water, either construct a dam so as to divert the water or excavate his ditch deeper, so as to reach and divert the water from the diminished quantity flowing in the natural water course. This would, of course, entail an additional expense upon the first appropriator.

To illustrate the question, let us suppose that upon a water course there is an average flow of water of 4 feet in depth; that the construction by the first appropriator of a ditch, the bottom of which is 2 feet below the surface of the water, enables him thereby to divert all the water he needs. Suppose that thereafter another appropriator constructs above the point of diversion by the first a ditch which appropriates 2 feet in depth of the water, and diminishes it so in volume that instead of flowing by the point of diversion by the first, 4 feet in depth, it now flows only 2 feet in depth. Still the quantity there flowing is sufficient to supply the needs of the first appropriator. It will be seen that the first appropriator can not, by the means then had, divert his amount of water, and there is necessarily entailed upon him an expense of either further excavation of the ditch or the erection of a dam in order to raise the surface of the water to a point at which it can be diverted into his ditch; and this additional expense is entailed by the act of the subsequent appropriator. It is not a question, as I have put it, of a deficiency in the supply of water, but it is merely a question of the right of a subsequent appropriator to diminish the volume of water flowing to such an extent that it can not be diverted by a prior appropriator by the means he then had. We think that it certainly can not be said that the first appropriator has the right to have the water flowing such a way that by his first means of diversion he can still continue his appropriation of the water. The whole policy of the law is, that all of the waters in the streams in this Territory should be used for mining, agricultural, and milling, and that there shall be no appropriation by anyone in a manner that shall prohibit subsequent appropriation by others, unless that subsequent appropriation leaves an insufficient quantity of water.

The court held that the title to irrigating water inheres in the land irrigated and not in the company diverting the water, and that priority of time at which the water was applied to beneficial use constitutes priority of right to use of said water, and that this priority was determined, not by the date of diversion from the river, but by the date of such actual beneficial use. Evidence was therefore taken to establish the date of actual irrigation of each tract of land under each canal, the date of such irrigation determining the beginning of the right to the quantity of water requisite for such irrigation. Each canal, therefore, was entitled in any given year only to such quantity of water as was necessary to irrigate the lands actually under cultivation, subject to similar rights of other lands previously acquired. The unit of area for this purpose was taken as 160 acres, or a quarter section, although fractions of such tracts were considered in rendering the decision, the lowest subdivision considered being 40 acres, or one-fourth of a quarter section. The duty of water was assumed as 64 miner's inches for a quarter section of land. A miner's inch was defined to be one-fortieth of a cubic foot per second, which made the duty of 1 cubic foot per second 100 acres. On this basis a decision

IRRIGATION SCENE.

was made, from which the following table was constructed, under the orders of the court:

Table showing for each year the number of quarter sections under each canal entitled to water from Salt River as per decree of court.

Year.	Salt River Valley Canal.	Maricopa Canal.	Tempe Canal.	San Francisco or Wormser Canal.	Utah Canal.	Mesa Canal.	Grand Canal.	Arizona Canal.	Total Number of quarter sections for each year.
1868	12¼	1							13¼
1869	22	6							28
1870	31¼	14¼							46
1871	48	24¼	5	8					85¼
1872	78¼	28¼	49	8					167
1873	90¼	29	57	12					188¼
1874	90¼	31	57	12					190¼
1875	90¼	32	57	12					191¼
1876	92¼	36	57	12					197¼
1877	95¼	41	57	22	7				222¼
1878	102	53	67	22	24	23	2		293
1879	104	65¼	70	22	24	30	15		330¼
1880	109	84¼	70	24	24	35	17¼		364
1881	116¼	102	72	24	24	43	18¼		400
1882	117¼	117¼	90	27	26	50	23¼		451¼
1883	118¼	124¼	90	28	38	59	43¼		501¼
1884	119¼	128¼	95	28	38	62	45¼		516¼
1885	120¼	133	98	28	38	73	46¼	43¼	580¼
1886	121¼	135	105	29	38	75	47¼	105¼	656¼
1887	122¼	134	113	31	40	82	47¼	192¼	765¼
1888	123¼	139	117	31	55	82	48¼	333¼	929¼
1889	123¼	139	117	31	55	82	48¼	350	946

The figures in the columns headed Salt River Valley Canal, Maricopa Canal, etc., indicate the number of quarter sections irrigated in the year designated in the column on the extreme left. Bearing in mind that priority in time denotes priority in right, it will be seen that although the oldest water rights are in the Salt River Valley and Maricopa canals, such priority extends only to the quantity of water necessary for those tracts which were irrigated previous to lands irrigated under other canals. Thus in 1873 the area irrigated under the Salt River Valley Canal was increased by 12 quarter sections over that of 1872, but the additional water necessary for this increase was secondary in right to all lands irrigated in 1872, whether under the Tempe, the Wormser, or the Maricopa Canal. It will be seen that 516½ quarter sections, or 82,640 acres, were irrigated in 1884, requiring under the adjudicated duty of water 826 second-feet. In addition to this, Hayden's mill was entitled to 1,100 inches, but this amount need not be deducted from the irrigating supply of the river, because the water from Hayden's mill returned to the river above the head of the oldest canals and could be rediverted by them for irrigation.

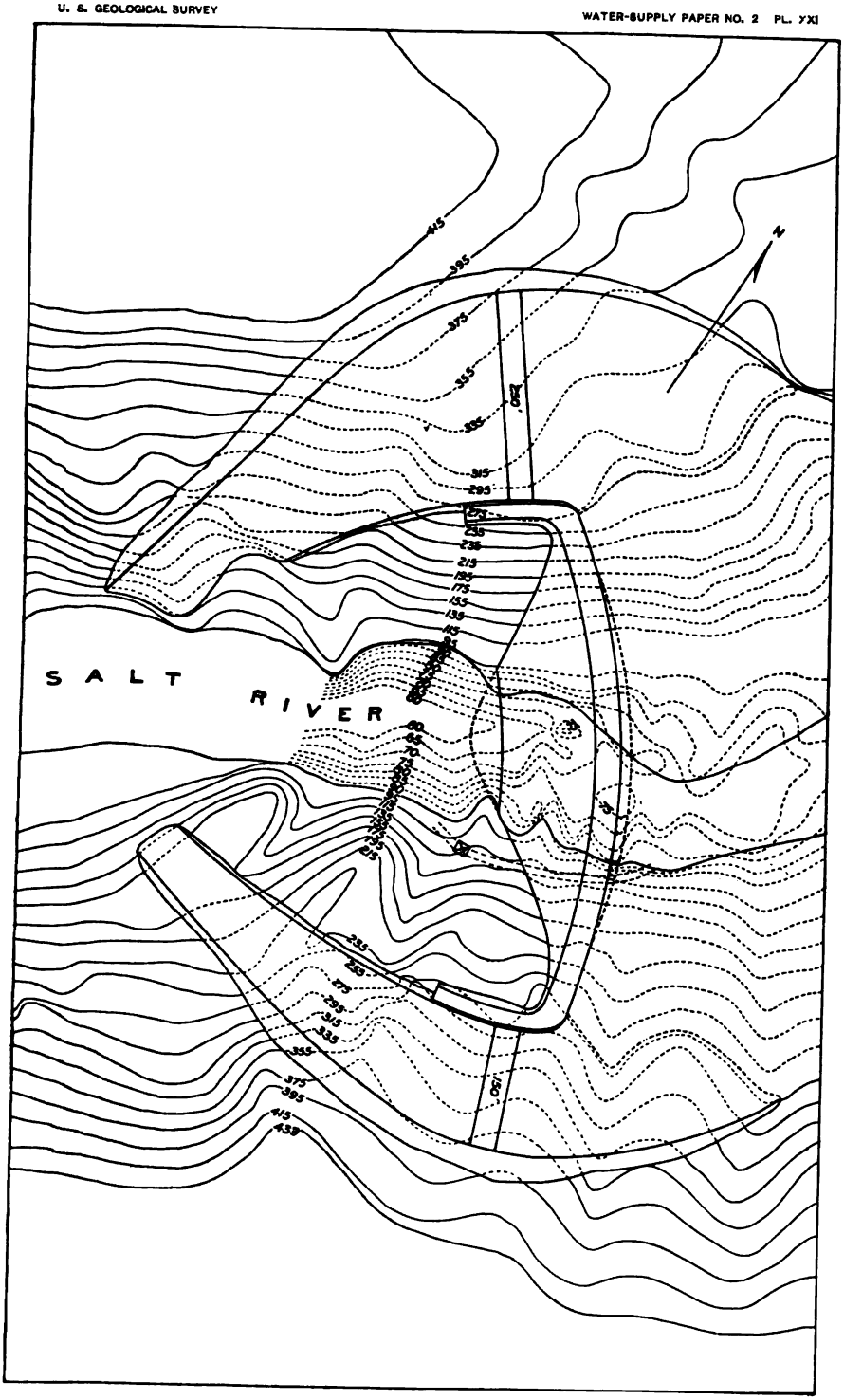
Considerable effort has been made by the later-constructed canals, particularly the Arizona and Mesa Consolidated, to establish claim to what is called the surplus waters or flood discharge of Salt River. These rights are of somewhat doubtful value for any purpose to which these canals can put them, for the high waters embraced by such claims are of short duration and can not be utilized to mature any crop. They are used for "soaking up" the ground during the period of high water in the hope that a portion of the moisture will be retained by the soil to mitigate the drought through the low-water season, when such waters can not be applied. It is obvious that such a use of waters is not a use at all, but a waste. It is not especially objectionable at present, except that in some instances farmers are thus encouraged to plant crops which can be matured only by the use of water obtained either illegally or through the generosity of some of the older proprietors. What standing such claims to the surplus waters can obtain in the courts remains to be seen. If they are sustained, the result will be disastrous to the future development of irrigation, for it is these surplus waters upon which any project for storage on the upper waters of the Verde and Salt rivers must largely depend. Such storage works will hold the surplus waters for use during the dry season, when they are most needed, but if title is held in the manner claimed, they will probably continue to be wasted as at present.

IRRIGATION WORKS PROJECTED.

Having noted the principal irrigating systems taking water from the Salt and Gila rivers, and reviewed in a general way the demands for water and the claims made upon the flow of these streams, it is pertinent to discuss at some length the attempts now being made to increase the available water by means of reservoirs and other works designed to save in part the waste water occurring in floods. The principal projects which have been surveyed by individuals and corporations or examined by the Government are known as the Rio Verde, Tonto Basin, Walnut Grove, Agua Fria, Cave Creek, Buttes, Lower Gila, and Queen Creek.

RIO VERDE.

This enterprise contemplates the storage of waters at the site on the Rio Verde known as the Horseshoe Reservoir, in T. 8 N., R. 6 E., Gila and Salt River meridian. The drainage area tributary to this reservoir is nearly 6,000 square miles. The proposed height of the dam at this point is 150 feet above the present surface of the river, and it will extend to a maximum depth of 25 feet to bed rock. It will be 386 feet long at the low-water line of the river, and 1,250 feet along the top. It is proposed to build this dam of a rock-filled type having side slopes of 2 : 3, made impervious on the water side by a sheet of asphalt pavement extending to bed rock. The spillway is situated over


SALT RIVER
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2,000 feet west of the dam and is separated from it by a mass of rock rising over 75 feet above the spillway. It will be about 1,000 feet long. This reservoir will have a length of about 6 miles, a surface area of 3,402 acres, and a capacity of 204,935 acre-feet, as shown by the following table, which gives the area and capacity for each 10 feet elevation of the surface:

Area and capacity of Horseshoe Reservoir.

Contours.	Area, in acres.	Acre-feet between contours.	Total capacity in acre-feet.
10	39	270	270
20	99	690	960
30	268	1,835	2,795
40	442	3,550	6,345
50	720	5,810	12,155
60	974	8,470	20,625
70	1,178	10,760	31,385
80	1,398	12,880	44,265
90	1,665	15,315	59,580
100	1,916	17,905	77,185
110	2,109	20,125	97,610
120	2,349	22,290	119,900
130	2,646	24,975	144,875
140	2,982	28,140	173,015
150	3,402	31,920	204,935

Work upon the dam itself has not yet been begun, but the outlet tunnel is completed. It is intended to divert the river through this tunnel when necessary to complete the foundations. The tunnel is 715 feet long, 12 feet in diameter, with open-cut approaches.

About 18 miles below the Horseshoe Reservoir the water is to be diverted from the river by a dam 90 feet high and 475 feet long, of the rock-filled type. Here the canal is to head with a bottom width of 25 feet, depth of water 8 feet, side slopes 1 : 1, and a fall of 0.0003. The estimated mean velocity is to be 3 feet per second and the capacity 800 cubic feet per second. This section is continued for a distance of 54 miles, a considerable part of the distance being through rough country, with very heavy construction. At the end of the 54 miles the bottom width is reduced to 20 feet, and this width is maintained 15 miles farther to the crossing of New River. At New River it is proposed to construct another reservoir, partly to impound the storm waters of this stream, which is ordinarily dry, and partly to receive the waste waters from the canal. The proposed dam for this reservoir will be 100 feet high, with a top length of 1,800 feet, which it is said will impound over

100,000 acre-feet of water. It is not intended to construct this reservoir at present, but it is contemplated as a future possibility after the development of the upper portion of the project. It is proposed to continue the canal from this reservoir on a grade line across the Agua Fria River, round the base of the White Tank Mountains, and across the Hassayampa, and to utilize another reservoir west of the Hassayampa, just above the Buckeye Canal, near the Four Buttes, which it is proposed to fill by a lateral feeder from the main canal. The land under this canal between Agua Fria and the Hassayampa rivers, as shown on the map, it is also proposed to irrigate from the Agua Fria Land and Water Company's works. The conflict of interests here, however, is more imaginary than real, as there is abundant good land to utilize all the water that can be furnished by both these projects and any others that may be constructed.

The estimated cost of the dam for the Horseshoe Reservoir is $600,000; the diversion dam is estimated to cost $200,000, and the canal to the Hassayampa is estimated to cost about $1,200,000, making $2,000,000 in all, exclusive of the two reservoir sites in the plains. It is estimated that from the head-gates to the Agua Fria River the canal covers an area of 125,000 acres of irrigable lands, including a very desirable tract of nearly 50,000 acres in Paradise Valley. West of the Agua Fria the land to be irrigated is an almost unbroken plain of sandy loam, and comprises more than 125,000 acres above the Buckeye Canal and east of the Hassayampa. As above stated, this project is under construction, the greater part of the work already done being upon the canal. The magnitude of the undertaking, the natural difficulties to be overcome, and the prevailing business depression combine to render its prosecution a matter of peculiar difficulty.

The company claims to have sold water rights for about 100,000 acres at prices varying from $10 to $18 per acre, paid for at the rate of $1 down and $1 per year thereafter. The payment of this $1 per acre each year is considered to be a sufficient compliance with the law requiring a person entering desert land to expend a certain amount in the use, irrigation, reclamation, and cultivation of the land. After the works are constructed the owners of the water right are to pay a certain amount per quantity of water used, the unit of measurement being the cubic foot. The rate charged is to be a gradually increasing one from $1.21 up to $2.42 per acre-foot after ten years. The maximum amount of water which can be demanded in any one year is at the rate of 2 acre-feet for each acre irrigated.

THE TONTO BASIN PROJECT.

Just below the junction of Tonto Creek with Salt River, near the line between Gila and Maricopa counties, Salt River passes through a deep, narrow gorge of solid rock. Above this point both streams flow through wide, level valleys, which are settled and cultivated to

VIEW IN CANYON OF SALT RIVER BELOW MOUTH OF TONTO CREEK.

a considerable extent. The Hudson Reservoir and Canal Company has made surveys and estimates, contemplating the construction of a dam at this point (fig. 9) about 215 feet high from bed rock and 610 feet long on top, which it is claimed will give a reservoir capacity of over 800,000 acre-feet. A spillway is to be cut around each end of

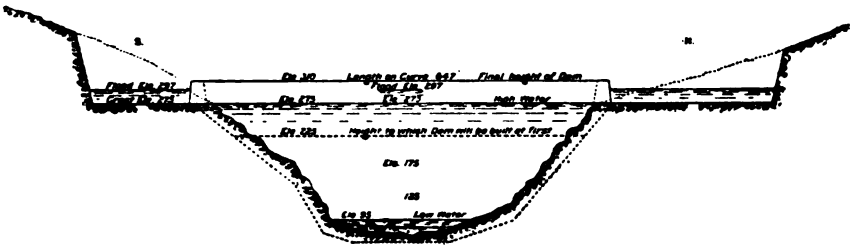


FIG. 9.—Elevation of proposed dam on Salt River.

this dam, as shown in Pl. XXI. It is proposed, first, to build a dam on an ogee section (fig. 10, *a*) about 140 feet in height, heavy enough to form the base of the dam of the full height, and to allow the flood water to pass over its crest after the reservoir fills. After the waters impounded by this reservoir have been disposed of the dam will be completed (fig. 10, *b*) and the additional waters will be sold.

Several lines have been surveyed for the location of a canal to con-

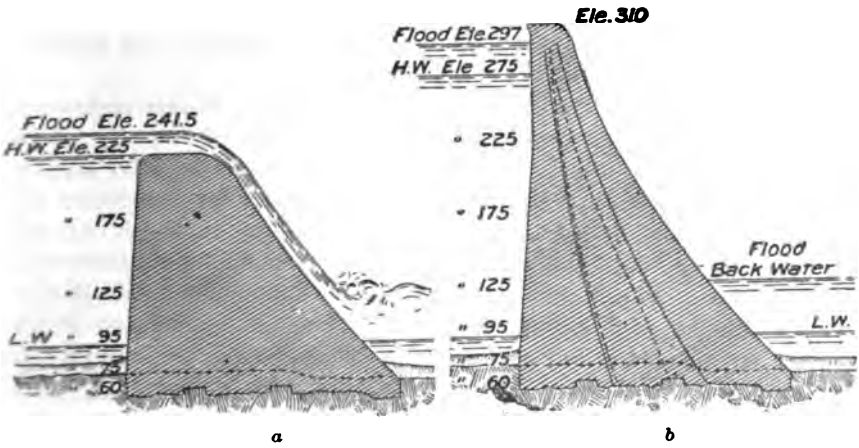


FIG. 10.—Profile of proposed dam on Salt River. *a*, first construction; *b*, completed.

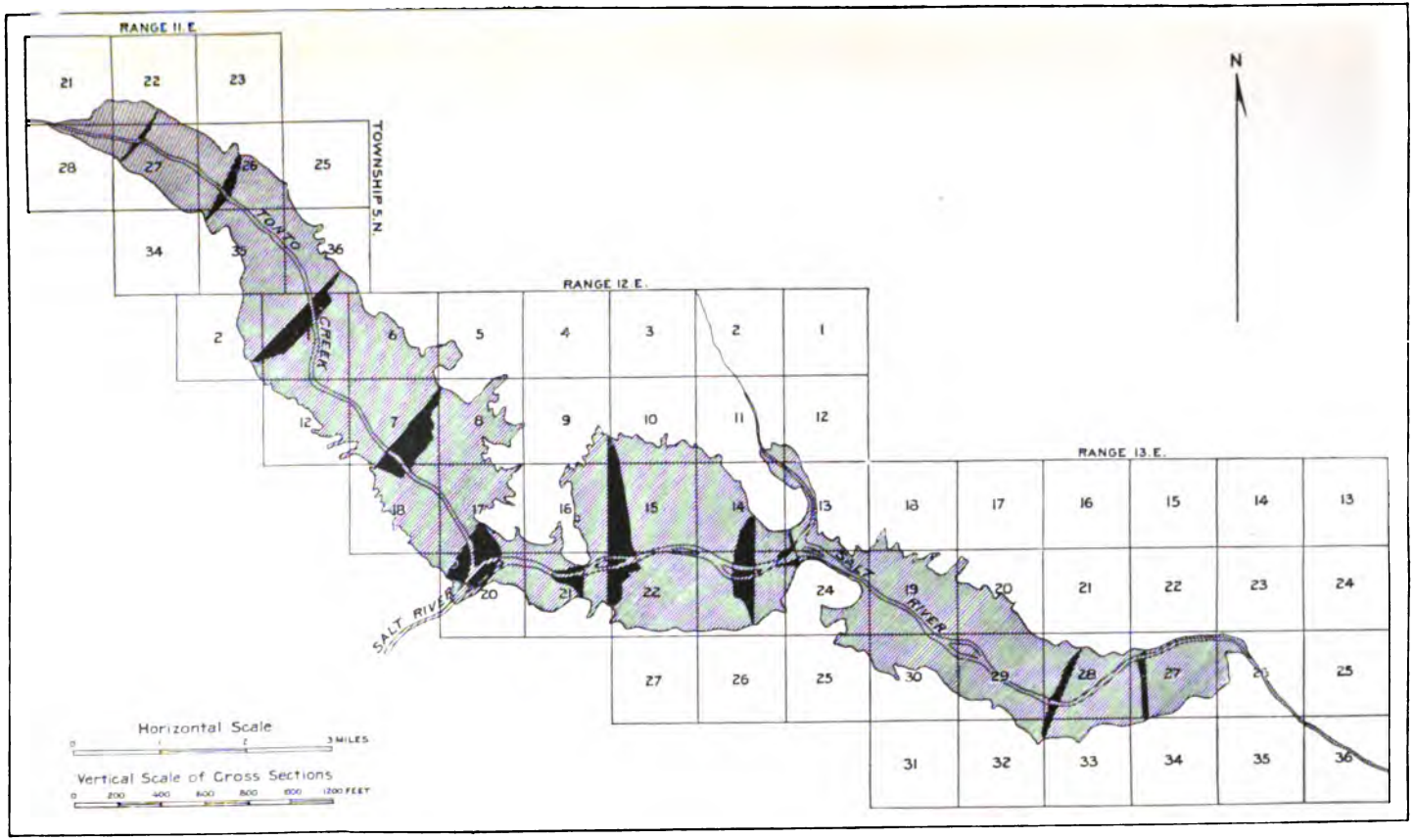
duct these waters to irrigable lands on the south side of the river, and it has been shown that by diverting the waters well up in the canyon of Salt River they can be delivered high enough to water a large tract of land at present not under canal and to irrigate the greater portion of the valley lands on the Pima Indian Reservation. This involves a

large amount of costly construction in the canyon, and it is not probable that such a line will be found advisable. Large tracts of uncultivated land are already under existing canals, particularly the Arizona, the Mesa Consolidated, and the Highland canals. Many of the older canals have also under them considerable tracts of uncultivated lands for which they hold no water right, and whatever waters are left after supplying all these demands can be distributed from the line somewhat higher and parallel to the Highland Canal without involving much heavy construction.

It would probably be impossible to find anywhere in the arid region a storage project in which all conditions are as favorable as for this one. The capacity of the reservoir, in proportion to the dimensions of the dam, is enormous. The lands to be watered are of remarkable fertility, in a climate which may be classed as almost semitropic, and are vastly greater in area than the water can supply. To a considerable extent they are already settled upon, and the water is in lively demand. The character of rock at the dam site is said to be excellent for the construction and foundation of the dam. There is tributary to this reservoir about 5,756 square miles of mountainous country, ranging in altitude from 2,000 to 12,000 feet, and including some of the best drainage area in Arizona. Many of the tributaries of Salt River find their source at the foot of the bold escarpment of the Mogollon mesa. Tonto Creek, for instance, heads at the foot of this mesa with the volume of a very considerable rivulet within a few hundred yards of the divide. Such streams evidently obtain considerable water supply from the precipitation which falls north of the divide, as pointed out on page 16.

These facts indicate that the watershed tributary to this reservoir is not only large but favorable to a high percentage of run-off. It is doubtful, however, whether the immense reservoir capacity above referred to could be filled in the driest years, and what proportion of its capacity should be held as a reserve for years of minimum run-off can not be determined exactly without a long series of measurements of the discharge of Salt River between the mouth of the Verde River and the mouth of Tonto Creek. Such measurements have been roughly carried on for over a year by the Hudson Reservoir and Canal Company, and the results, so far as observed, are given on page 39; but the series is too short to justify a positive expression on this point. There can be no doubt, however, that in this reservoir site lies one of the most important possibilities for the future of the agriculture of southern Arizona.

Pl. XXIII shows the outlines of this reservoir site as surveyed. The shaded portions represent cross sections on the lines indicated.



TONTO RESERVOIR SITE, SHOWING ELEVATIONS OF TEN CROSS-SECTIONS OF THE RESERVIOR.

Area and capacity of Tonto Reservoir.

Height above low water.	Capacity, in acre-feet.	Surface, in acres.	Elevation above sea level.
25	4,400	330	1,950
30	6,100	420	----------
35	9,000	570	----------
40	11,900	730	----------
45	16,200	890	----------
50	20,000	1,030	1,975
55	26,900	1,280	----------
60	33,300	1,510	----------
65	42,000	1,740	----------
70	50,700	1,980	----------
75	62,100	2,300	2,000
80	73,500	2,610	----------
85	88,500	3,010	----------
90	103,600	3,430	----------
95	122,700	3,820	----------
100	141,800	4,210	2,025
105	164,700	4,610	----------
110	187,700	4,990	----------
115	214,700	5,430	----------
120	241,800	5,860	----------
125	272,800	6,210	2,050
130	303,900	6,570	2,055
135	338,600	6,950	----------
140	373,400	7,350	----------
145	413,000	7,930	----------
150	453,000	8,530	2,075
155	498,000	9,110	----------
160	544,000	9,680	----------
165	594,000	10,170	----------
170	645,000	10,680	----------
175	701,000	11,240	2,100
180	757,000	11,750	2,105
185	820,000	12,300	----------
190	880,000	13,000	----------
195	950,000	13,600	----------
200	1,020,000	14,200	2,125

WALNUT GROVE RESERVOIR.

A storage reservoir was built on the Hassayampa River just below the settlement of Walnut Grove in 1888. The dam (fig. 11) was 420 feet long on top, 138 feet wide at bottom, 15 feet in width on top, and 110 feet high. As shown in Pl. XXIV, it was of the rock-filled or placer-mining type, consisting of a front and back wall of dry rock carefully laid with loose rock filling between. A wooden sheath covered the water slope to make it water-tight. This covering was fas-

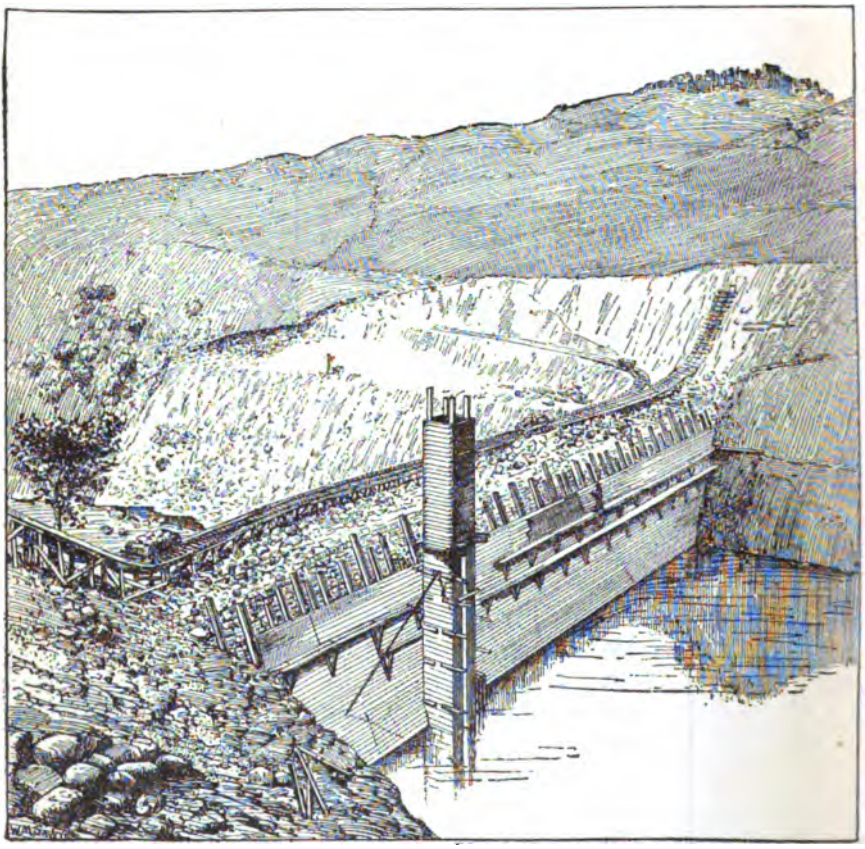


FIG. 11.—View of Walnut Grove dam.

tened to vertical stringers about 8 by 10 inches, which in turn were bolted to the projecting ends of heavy logs built into the upper face, the stringers being about 4 feet apart (fig. 12). The sheathing consisted of two thicknesses of 3-inch planking, with tarred paper laid between the two. The outer face was calked and covered with paraffin paint. Owing partly to the insufficiency of the spillway and partly to its becoming obstructed with driftwood, the great flood of

WALNUT GROVE DAM.

February, 1890, overtopped this dam, causing it to fail. The capacity of this reservoir has been variously estimated at from 7,000 to 14,000 acre-feet. Its destruction caused the loss of twenty-six lives and a considerable quantity of property in the valley below. A new reservoir could doubtless be constructed on the same site which would redeem at least 5,000 acres of the land.

AGUA FRIA PROJECT.

The Agua Fria Water and Land Company's project contemplates the construction of two reservoir dams and one diversion dam on

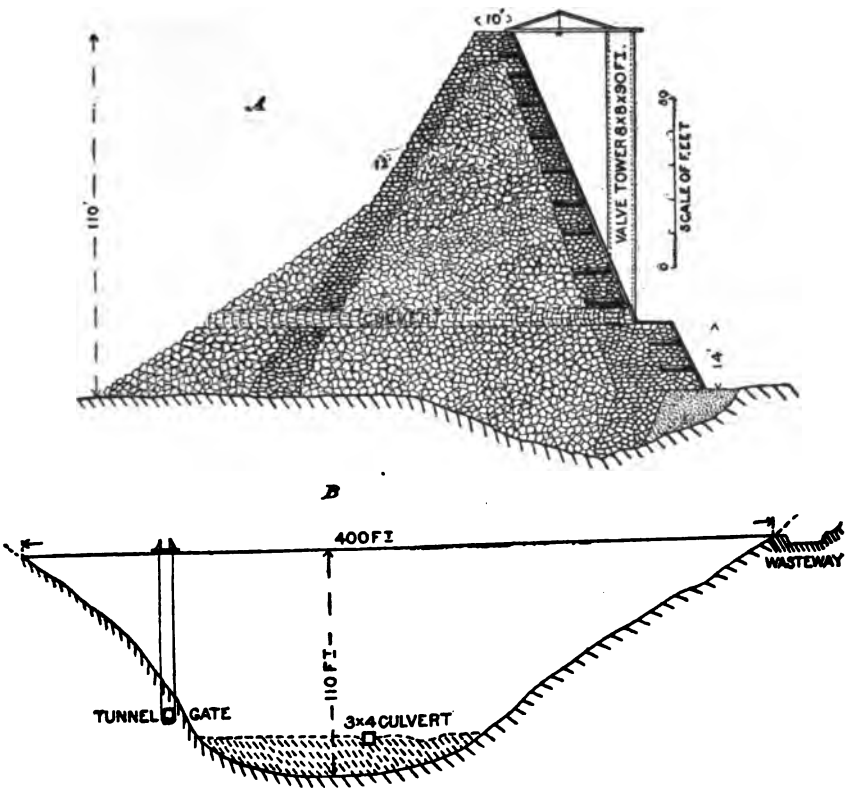


FIG. 12.—Cross section and elevation of Walnut Grove dam.

Agua Fria River. The diversion dam, a view of which is given in Pl. XXV, is already nearly completed. It is built of rubble masonry, laid in mortar made with a natural cement burned 25 miles southwest of the dam site, at the foot of the White Tank Mountains. The masonry cost about $4 per cubic yard, the stone being placed by cable conveyor, as shown in the plate. The total length when completed will

be 650 feet, the greatest height above the creek bed 40 feet, in addition to which the deepest excavation to bed rock was 40 feet. The greatest width on bed rock is 53 feet. A spillway is to be provided around the west end. The upstream or back of the dam is vertical. The lower batter is 12½ in 20. Two sluices are left at the surface of the stream bed, each 4 feet wide by 6 feet high, to dispose of the flowing waters. The top width when completed will be about 8 feet. In October, 1895, a great flood came down the river, which the sluiceways were unable to discharge and which poured over the dam for several hours to a depth of more than 8 feet, finally carrying out a portion of the recently completed masonry, about 12 by 100 feet, near the west end of the dam. The portion remaining below that carried away exhibits a smoothly plastered surface with no evidence of fracture or indication of having been bonded in any way to the destroyed section. The rubble masonry contains numerous horizontal joints finished and plastered as smooth as though intended for a floor, apparently diminishing the bond with the next course above. This seems to be in direct contravention of good engineering practice, and to account in a measure for the failure of the portion of the dam above mentioned.

The canal heads at the east end of the dam in a cut 16 feet deep in solid rock, and is constructed for a distance of about 4 miles. At this point it is intended to carry the canal across the river in a flume 700 feet long, and to extend it in a southwesterly direction around the foothills of the White Tank Mountains toward the Hassayampa River. The constructed portion of the canal is 18 feet wide on bottom, and is intended to carry 8½ feet of water. The grade is 0.0004 or 2.11 feet per mile, and the capacity is intended to be 400 cubic feet of water per second. A large lateral is to be taken from the east side of the main canal about 2½ miles from the head, to extend southward for the service of the lands on the east side of the river.

The first reservoir dam is to be located 1¼ miles above the diversion dam, at an old stage station known as Frog Tanks. A fairly good dam site occurs here, with rock abutments, and the bed rock is said to be near the surface. It is proposed to build this dam to a height of 100 feet, and it is claimed that this will impound about 50,000 acre-feet of water. No considerable amount of work has been done upon this dam other than excavating pits on the slopes and making soundings to ascertain the depth to bed rock in the bed of the river. Quarries have been opened and a large amount of rock has been quarried and prepared for the work. The construction of this dam is to follow immediately after the completion of the diversion dam.

Eight miles above this place another dam site is located, in a gorge through solid rock, 262 feet wide at the bed of the river, and but 500 feet wide at a height of 200 feet. It is said that this basin will impound, with a dam 150 feet high, over 150,000 acre-feet of water.

DIVERTING DAM ON THE AGUA FRIA.

The plans of this irrigation project appear to be open to criticism, for by continuing the canal 1¼ miles farther up the canyon it would have reached the lower reservoir dam site, which is the next structure contemplated in the plans, and which would have served as a diversion dam, and the cost of the dam already constructed might thus have been saved. The construction of the canal through this distance would be expensive, as the country is rough, but it certainly would not approach in cost that of the diversion dam. Moreover, when in use the diversion dam will require to be filled to a height of nearly 40 feet above the bed of the creek to reach the intended height in the canal. This will form a pond of probably 40 or 50 acres constantly exposed to evaporation in this warm and arid climate. This loss is worth considering, for the water supply is the limiting feature of this enterprise, the capacities of the reservoirs and the land to be irrigated being relatively much greater than the water supply to be depended upon.

CAVE CREEK PROJECT.

The Pennsylvania Irrigation Company proposes to build a dam 100 feet high in the canyon of Cave Creek, which it is said will form a reservoir of more than 100,000 acre-feet capacity. The water is to be diverted about 7 miles below and used in the irrigation of the lands in Paradise Valley above the line of the Rio Verde Canal. As this drainage area is estimated to be only about 200 square miles, it seems improbable that this area will furnish sufficient water to justify the construction of a reservoir of this capacity; but a reservoir can doubtless be built at this point which will impound all the waters that can be depended upon from its drainage, and the land to be watered is abundant and excellent.

THE BUTTES RESERVOIR.

At a point about 14 miles east of Florence the Gila River passes between two buttes locally known as "The Buttes." For many years it has been proposed to build a dam at this point to store the flood waters of the Gila River for the reclamation of the arid plains below. This project was investigated by the writer in 1896 in connection with the water supply for the irrigation of the Pima Indian Reservation.[1] A detailed survey was made of the gorge through which the river passes, for the purpose of determining the best point for a dam and its dimensions and cubical contents. The scale adopted was 50 feet to an inch and the contour interval 2 feet, except where the slopes were too precipitous for this interval, when only 10-foot contours were drawn. After the completion of this survey the reservoir site to an elevation 200 feet above the bed of the river in the gorge was mapped

[1] Fifty-fourth Congress, second session, Senate Doc. No. 27.

on a scale of 5 inches to a mile in 10-foot contours. The reservoir capacities obtained by this survey are as follows:

Area and capacity of The Buttes Reservoir.

Contour flow line.	Area, in acres.	Capacity of section, in acre-feet.	Total capacity, in acre-feet.
10	20	100	100
20	71	450	550
30	229	1,500	2,050
40	397	3,130	5,180
50	533	4,650	9,830
60	741	6,370	16,200
70	928	8,345	24,545
80	1,105	10,165	34,710
90	1,329	12,170	46,880
100	1,566	14,475	61,355
110	1,769	16,675	78,030
120	2,029	18,990	97,020
130	2,367	21,980	119,000
140	2,746	25,565	144,565
150	3,149	29,475	174,040
160	3,602	33,755	207,795
170	4,118	38,600	246,395
180	4,609	43,635	290,030
190	5,133	48,710	338,740
200	5,651	53,920	392,660

Eleven soundings for bed rock were made at the dam site by driving iron rods into the gravel. What was supposed to be bed rock was reached at a maximum depth, near the center of the river, of 65 feet. The site proposed for this dam is where the river enters the gorge (Pl. XXVI), between the end of a projecting ridge on the east and a solid igneous dike on the west. It is proposed to build the dam to a height of 170 feet above the bed of the river, or 235 feet from bed rock. The top width is to be 12 feet; the upstream or back slope is to be 1 in 20, the face slope 1 in 2 from the top to a point 80 feet below the top, and 2 in 3 from that point to bed rock, as shown in fig. 13. A spillway capacity of over 100,000 cubic feet per second is to be provided, partly to the east and partly to the west of the dam. Both spillways will discharge their waters clear of the dam. This reservoir will have a capacity, as shown in the above table, of 205,000 acre-feet above the outlet tunnel, which will be about 30 feet above the bed of the stream. The outlet tunnel will pierce the hill to the southwest of the dam, and will be about 1,200 feet in length.

VIEW OF DAM SITE AT THE BUTTES, GILA RIVER, LOOKING NORTH.

Another and larger tunnel will be cut through the ridge to the east of the dam, on a considerably steeper grade, and discharge on a level with the river bed, for use as a sluiceway in clearing the reservoir of sediment. The discharge of the Gila River was measured by the United States Irrigation Survey for the year ending August 31, 1890.

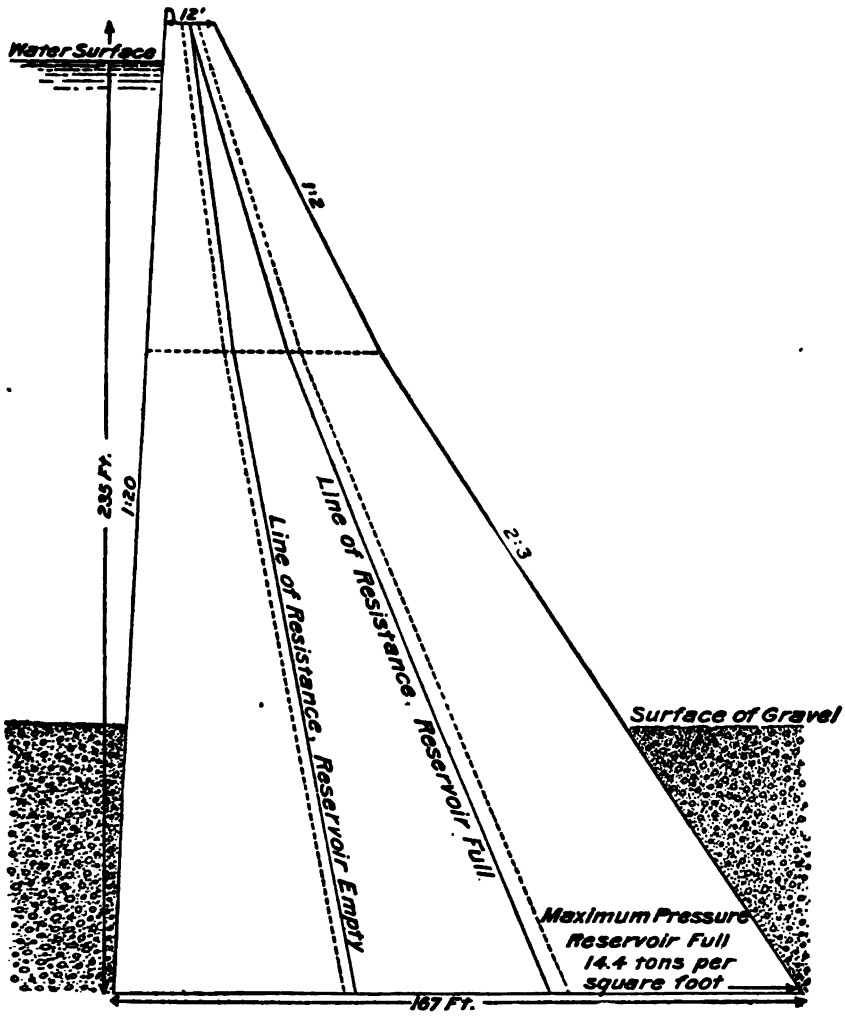


FIG. 13.—Profile of proposed dam at The Buttes.

The results of this measurement are given on page 40. Measurements for irrigation investigation, under the auspices of the Indian Bureau, were begun by the writer at the same point December 10, 1895, and continued until July 1, 1896, and they have been continued since that date to the present time by the United States Geological Survey. Previous to this private parties endeavoring to establish

claim to this reservoir site took readings of gauge height and occasionally measured the velocity by the use of floats. With the data obtained in this manner, and by comparison with measurements made in 1896, the discharge of the river has been approximated from July to December. The results for 1895–96 are given on page 40, and a diagram of the discharge as actually measured is given in fig. 7. The area of this basin is so large, its topography so varied, the rainfall so small and erratic, and the evaporation so great that it is impossible to arrive at any conclusion from theoretical considerations as to the amount of run-off to be expected from it. This can be determined only by a long series of measurements. It is probable, however, that an area of 75,000 to 100,000 acres can be reclaimed by waters stored at this point. The cost of such reclamation would be something over $2,000,000.

QUEEN CREEK RESERVOIR SITE.

Queen Creek rises in the mountains to the eastward of Silver King mine, and, flowing in a general southwestern direction, leaves the mountains below Whitlow's ranch, and in ordinary years loses itself in the desert north of the Gila River Reservation. In times of extremely high and protracted floods the waters of this creek reach Gila River several miles below Sacaton Agency. At Whitlow's ranch the creek passes between two buttes, forming a narrow rocky gorge advantageously conditioned for a dam site, and above this point the valley spreads out in a broad basin favorable for storage. This project was investigated in 1896 in connection with the irrigation investigation[1] for the benefit of the Pima Indians on the Gila River Reservation, little being known of its possibilities when the field work began. A topographic map of the drainage basin was made on a scale of 1 mile to an inch, with contour intervals of 100 feet. Its area is 142.5 square miles, or 91,200 acres, 61 per cent of which lies above the elevation curve of 3,000 feet and 39 per cent below that curve. The reservoir site was surveyed on a scale of 5 inches to the mile, curves of 10 feet interval being inserted to an elevation of 140 feet above the bed of the creek at the dam site, which is topographically the limiting height of a possible dam at this site. The practical limit, however, is reached at an elevation considerably lower, owing to the meager water supply, which is limited by the small drainage area, the aridity of the climate, and the great evaporation to which the impounded waters would be exposed. The plans proposed provide for a dam 115 feet above the bed of the creek. It is to be built on the rock-filled plan, with a water slope of 1 in 1, a down-stream slope of 1 in 2, and a top width of 10 feet. (Fig. 14.) Upon the water slope is to be laid a sheathing of asphalt concrete, and from the upstream toe an impervious wall of cement rubble masonry is to be

[1] See report in Senate Document 27, Fifty-fourth Congress, second session.

ELEVATION OF PROPOSED DAM AT THE BUTTES.

carried down to bed rock, which, in the deepest place, is about 30 feet. An outer shell of carefully laid dry rock wall is to be built, which will be carried down to bed rock at the down-stream toe. Spillways will be excavated at each end of the dam, and it is from these that rock will be obtained for the construction of the dam. Little is known of the hydrographic possibilities of this basin, owing to the almost total absence of data on the subject. A record of rainfall ten months in duration was kept at Silver King, but its results appear to be of doubtful utility. Measurements of discharge were begun at Whit-

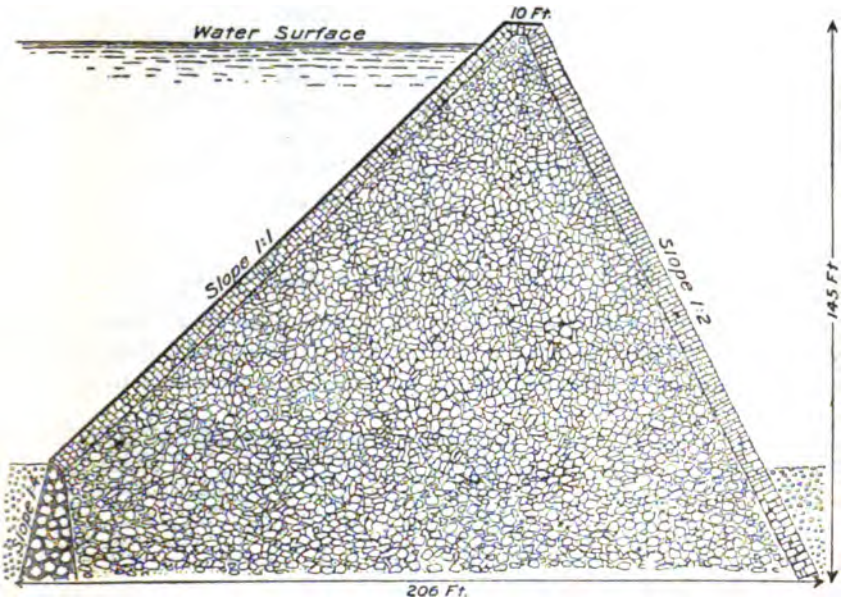


FIG. 14.—Profile of Queen Creek dam.

low's ranch in July, 1896. It is very difficult to make these measurements with any considerable degree of accuracy, owing to the extremely flashy character of the stream. Almost the entire discharge at this point is in the form of violent floods. It is estimated that a supply of about 10,000 acre-feet per annum can be depended upon from this project, sufficient to reclaim about 5,000 acres of land at a cost somewhere about $200,000. A table and diagrams of discharge of this stream may be found on page 42. An abundance of excellent land lies near at hand, with perfectly smooth surfaces and a maximum slope of about 40 feet to the mile.

Area and capacity of Queen Creek Reservoir.

Contour.	Area, in acres.	Capacity in acre-feet.
2,060	8	40
2,070	22	190
2,080	52	560
2,090	112	1,380
2,100	209	2,985
2,110	279	5,425
2,120	356	8,600
2,130	445	12,605
2,140	538	17,520
2,150	630	23,360
2,160	757	30,795
2,170	894	39,050
2,180	1,019	48,615
2,190	1,191	59,665

THE LOWER GILA STORAGE RESERVOIR.

This project contemplates the construction of a large dam on the Lower Gila in the gorge below Oatman and Cottonwood flats, not far from the railroad station of Sentinel. So great diversity of climate

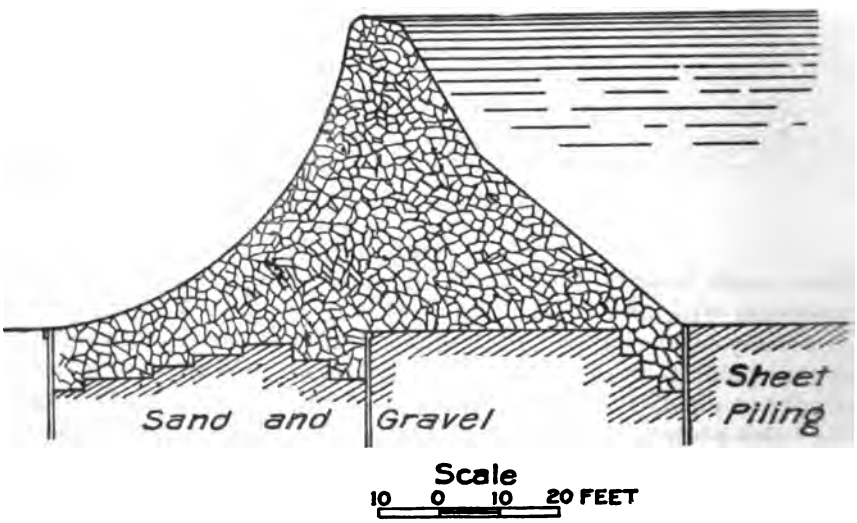
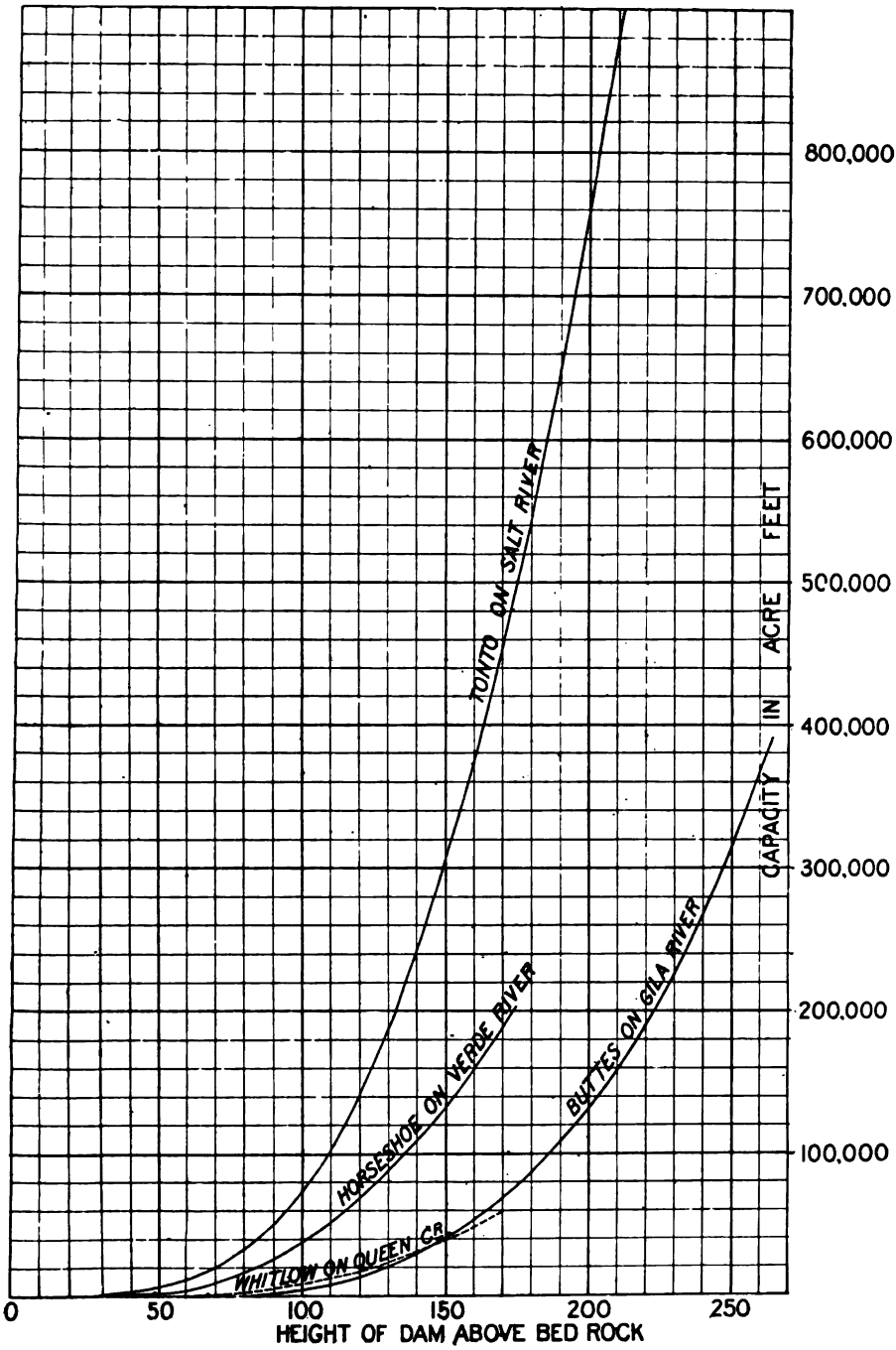


FIG. 15.—Section of proposed South Gila dam.

and topography is embraced by the drainage tributary to this reservoir that it is likely that it would receive a large run-off available for storage for irrigation and very materially increase the area reclaimable after all reservoirs in the upper portion of the basin are utilized.



COMPARATIVE DIAGRAM OF RESERVOIR SITES. GIVING CAPACITY OF EACH FOR VARIOUS HEIGHTS OF DAM.

Work on this reservoir was begun in 1892, but was discontinued, owing to financial difficulties, in the year 1893. It is the plan at present to construct at this point a dam 50 feet in height, a section of which is shown in Fig. 15. It is to be an overflow dam, protected on both faces with asphalt concrete. Seepage under the dam is to be cut off, so far as possible, by three rows of fluted sheet piling, one row at the toe, one at the axis, and one at the heel of the dam. This dam is to be utilized also as a diversion dam to raise the waters into the proposed canal, which will be taken out about 30 feet above the natural bed of the river, leaving 20 feet storage capacity above the bottom of the canal. The amount of this storage capacity is not known, but is undoubtedly great.

FUTURE DEVELOPMENTS.

Further development of irrigation in Arizona by the simple diversion of water from the Gila River and its tributaries is impossible. As already indicated, the dry-weather flow of these streams is over-appropriated. The area irrigated from such streams can be increased by more economical use of the water now claimed, but the actual water supply for irrigation can be increased only by storage and in some degree by the development of underground sources.

NATURAL ADVANTAGES.

The vast extent of land in southern Arizona of surpassing fertility, admirably situated for irrigation, and with a climate the aridity and warmth of which make it at once exceptionally healthy and marvelously productive, and depending for its development and reclamation solely upon the practicable water supply, renders the item of water supply of vital importance to the future history of the Commonwealth. It is impossible in the present state of knowledge regarding this question to make even an approximate computation of the extent to which this water supply can be increased. Enough is known, however, to give to a summary of the known possibilities considerable interest and some scientific value. Unquestionably the main reliance for the increase in water supply is the storage of storm and winter waters and those of the season of melting snows, to be held and allowed to flow upon the land only as needed, instead of flowing to the sea, or of being applied for a short time in excess only to evaporate.

STORAGE OF FLOODS.

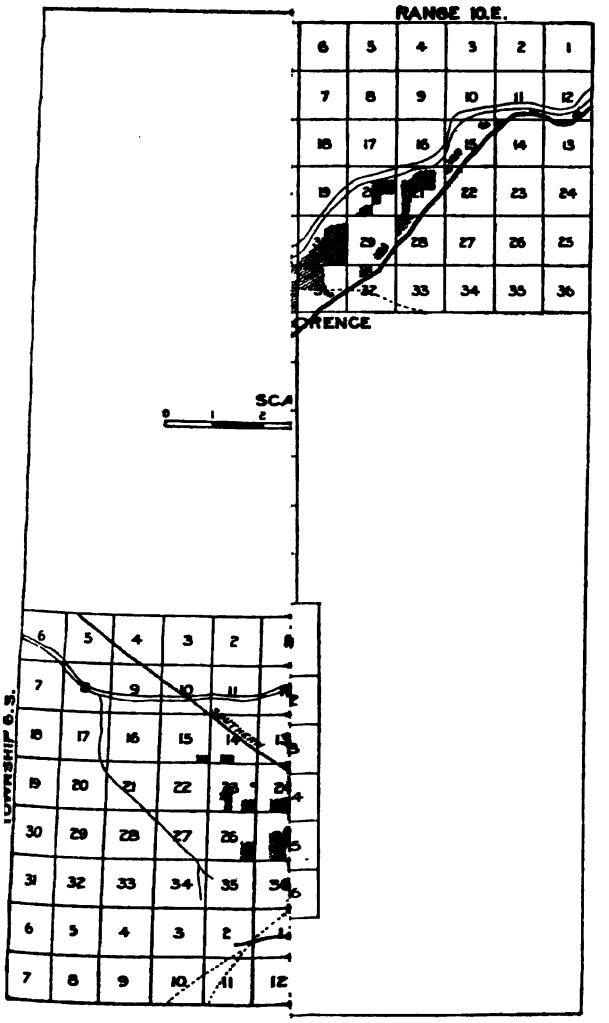
In some respects the topographic and climatic conditions in Arizona are peculiarly favorable for the complete utilization of its hydrographic possibilities. Few sections of the country are so well supplied with excellent reservoir sites favorably situated for the conservation of the surplus waters well above the areas to be irrigated. These favorable

conditions seem to apply not only to the location and great capacity of the reservoir sites, but to their engineering practicability.

This is a point the importance of which is realized by few persons who have not made irrigation engineering a specialty. The impression seems to be well-nigh universal that wherever a locality is provided by nature with surplus waters that are discharged in torrents and wasted, such waters can be stored and entirely utilized for irrigation. As a matter of fact, the truth of this proposition is the exception rather than the rule. This is chiefly due to the scarcity of practicable topographic conditions for the construction of reservoirs at the place where needed. The storage of water for domestic use in cities is often accomplished where natural conditions are by no means favorable, because water for this purpose is far more valuable than it is ever likely to be in any part of the world for general irrigation purposes. While it may be practicable and economical in some cases for a city to pay tens or even hundreds of dollars per acre-foot for water for domestic use, any such price is absolutely prohibitory where the water is intended for irrigation on a large scale, even in those parts of the world where irrigation is brought to greatest perfection, where products are of the most exceptional nature and highest value, and water commands the maximum price. But even in the case of city supplies, it is by no means practicable in all cases to construct storage reservoirs at the required height within practical limits of expense.

It will thus be seen that for the storage of water for irrigation the existence of peculiar and favorable topographic and geologic conditions for the construction of reservoirs is of no less importance than the existence of waters to be stored. A basin of large capacity, capable of being closed by a structure of small dimensions and unquestionable safety, or if naturally already inclosed, capable of being pierced by a tunnel or cut for drawing off its waters, must exist at an elevation sufficiently low and in a locality convenient for the reception of the waters to be stored, and sufficiently elevated and convenient for its waters to be carried, within practicable limits of cost, upon the lands to be irrigated. Such reservoirs, furthermore, must be of considerable depth; otherwise the great bulk of the stored waters will be lost by evaporation before they can be utilized. This is peculiarly true of Arizona, on account of the excessive aridity and heat of its climate. Even with the most favorably conditioned storage sites this item of evaporation always curtails the efficiency of a reservoir site and places a limit upon its utility for the purposes intended. The less the value of the water impounded the more favorable must be those topographic conditions, but for any purposes of irrigation they must be so favorable as almost to be topographic curiosities, and such are of comparatively rare occurrence.

Another element of error in the popular assumption above referred to arises from the fact that the great floods which bear such immense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quantities of water running to waste and which make such a strong impression on the public mind are so infrequent in occurrence and so enormous in volume that their storage and complete utilization are impossible. The observation of these great floods, such as those of 1891, in both the Salt and the Gila rivers, produces an impression upon the popular mind that the possibilities of irrigation by storage are vastly larger than in fact they really are. Even assuming ideal conditions regarding the existence and location of feasible reservoir sites, we are forced by a study of the facts to the reluctant conclusion that such great floods bear no relation to the extension of irrigation by means of storage except to imperil the works. As before stated, these great floods occur only once or twice in a great many years, and irrigation can be extended only in approximate proportion to the supply of water that can be obtained in the driest years. To a certain extent dry years may be reenforced by the conservation of the waters from years of excessive run-off. Of course, the reservation of a large surplus over and above that required for irrigation in the year of great run-off requires the provision of extensive storage capacity and consequent increase in the cost of the works, but a limit to the utility of this method is quickly reached, especially in the climate of Arizona, by the heat and aridity there prevalent.

The potential evaporation is equivalent to a depth of nearly 8 feet in this region, and a reservoir in which the reserve storage filled it only to a depth of 8 feet would be entirely evaporated before the next season. If the reserve storage extended to a depth of 16 feet, it would be all lost before the second year was reached. To tide over a series of dry years a reservoir of great depth is necessary. When we consider the fact that all storage reservoirs which it is practicable to construct for purposes of irrigation have their greatest areas in the upper contours, it will be seen that to subtract 8, 16, 32, or 40 feet from the upper zones of such a reservoir is to lose an enormous proportion of its stored contents. For instance, in the areas and capacities of the reservoir surveyed at The Buttes, given on page 72, we find that for a depth of 150 feet the area of the reservoir is 3,149 acres and its capacity 174,000 acre-feet. Should it be attempted to hold such a reservoir filled with water for a period of say four years, we should have an evaporation of at least 30 feet from its surface, which would lower it to the 120-foot contour, at which the capacity is 97,000 acre-feet, or a little more than one-half the quantity which was held as a reserve. Should it be desired to hold a depth of 100 feet in the reservoir as a reserve for use in dry seasons, we find that in a period of four years, assuming the evaporation in that time to be 30 feet, the amount would be reduced from 61,355 acre-feet to 24,545 acre-feet, a loss of about 60 per cent. If the depth of reserve storage were adopted as 70 feet, we should have a capacity of 24,545 acre-feet, which would be reduced by four years' evaporation to about 5,000 acre-feet, or

about 21 per cent, and another year would practically exhaust it. In the Sweetwater Reservoir, in southern California, 90 feet in depth, 80 per cent of the capacity of the reservoir is within the upper 30 feet of height and 40 per cent within the upper 10 feet.

It will be readily seen that the practical utility of a reserve storage is limited to three or four years, even with very deep reservoirs. With comparatively shallow reservoirs no such use is possible. Such great floods as occur only once or twice in ten or twenty years can not be held, even with unlimited storage capacity, to reenforce the years of minimum run-off, which of course occur at essentially similar intervals, and the meager observations at hand seem to indicate that they are not needed in the years in which they occur, as such years are likely to yield more than the average quantity of run-off, independent of such floods. On the other hand, they are a constant menace and a positive peril to the stability and perpetuity of the reservoir, owing both to their great magnitude and the great difficulty of determining what this magnitude is. Enormous and very expensive facilities must be provided for carrying them out of the reservoir without injury to the dam.

SILTING OF RESERVOIRS.

One of the most difficult problems presented in the storage of these great torrents is the enormous quantities of rocks, gravel, sand, mud, and silt which they carry into the reservoir, and even though no part of the flood may be held, the load of solid material is deposited and contributes to fill it and destroy its storage capacity. These terrible torrents, useless and dangerous as they are, contribute the major portion of the solid matter which is caught by such reservoirs, and this is one of the most serious and difficult problems to be solved by the irrigation engineers in southern Arizona. The amount of solid material brought down in this manner can be learned only by impounding and measuring it. Measurements of matter carried in suspension have been made on the Mississippi, on the Potomac, on the Rio Grande, and on streams in California, but even if these streams could be shown to bear any fixed relation to the torrents which it is proposed to control in Arizona the problem would still be unsolved, as an unknown quantity of such material is rolled along the bottom. This is proved by the large numbers of bowlders, small rocks, and gravel they carry which never could be held in suspension. Careful surveys have been made of new reservoirs in California with this problem in view, and after a lapse of several years a resurvey will doubtless furnish valuable information, but this is not available at the present time. The amount of solid material carried by the torrents of southern Arizona can be learned only by impounding it. As it is considerable, it is obvious that a reservoir built on such a water course will eventually fill with solid matter unless means are provided for its removal. No entirely efficient plan for this purpose has ever been put in operation.

It is usually assumed, and often with truth, that the life of the reservoir is sufficiently long to justify its construction, even though it will eventually fill and have its usefulness destroyed. The amount of material carried by streams in southern Arizona, especially in the summer floods, is too large and the necessity of the reservoir to the life of the district to be irrigated from it is too vital to justify this convenient solution, or rather evasion, of the problem.

At least one eminent engineering authority has expressed an opinion that such a reservoir, even when filled, would retain about 30 per cent of its available storage capacity in the voids of the material deposited. It would seem, however, that this opinion is entirely without foundation. The fluctuating character of such streams, as well as the widely variant specific gravity of the material carried, insures such a mixture of materials in regard to their fineness that the proportion of voids would be much smaller than in a body of sand or other material of approximate uniformity of size. By filling any given volume with coarse materials, such as bowlders, filling the voids of these bowlders with coarse gravel, these voids again with finer gravel, and so on through the coarser grades of sand to the very finest silt, using of each material just enough to fill the larger voids in the coarser material, a mass will be produced with an extremely small percentage of voids. This is roughly the course pursued in the manufacture of concrete, and apparently would be approximated by nature in the case of a mountain reservoir. But whatever the percentage of voids, the water contained therein would not only be held strongly by the forces of capillary attraction and surface tension, but the friction in the containing material would resist its escape so powerfully that even that portion which could be drawn off would escape with extreme slowness. While probably such a reservoir might store and yield for use a considerable quantity of water, it is clear that this quantity could not aggregate anything like 30 per cent of the original capacity of the reservoir.

It has been proposed to sluice out such material by providing large openings from the reservoir and occasionally allowing a large volume of water to rush out and carry the collected material with it. This method has been successfully employed in diverting dams for keeping open the approaches to the head gates of canals. It is also extensively employed in cleansing reservoirs in Spain. But experience has shown that only a comparatively small area is cleaned by this method, reaching on a steep grade for a moderate distance above the scouring sluices. For clearing a reservoir several miles long it is manifestly inadequate and must be supplemented by something else.

Another method of counteracting the tendency of the reservoir to fill is by enlarging its capacity. This method is not always possible. Where possible it is always expensive, and so far from being a solution of the problem, merely postpones the date when some means

must be adopted of clearing out the impounded silt. It may, however, in some cases be advisable, where the expense is not too great, as the combined effect of raising the dam higher and of its filling with silt is to increase the altitude of the surface of the silt above the scouring sluices, and, by increasing the velocity of the water which is used in sluicing out the silt, to increase the efficiency of that means of cleansing the reservoir.

The removal of the accumulated débris by the ordinary methods of excavation is clearly out of the question. No community in the world can afford to pay for an acre-foot of storage capacity for the purposes of irrigation any sum approaching the cost of an acre-foot of excavation by the ordinary methods. A method is here suggested, however, which it is believed might be applied in many cases, and when properly adapted to the topography and hydrography of the locality, would, it is believed, be effective in some cases within practicable limits of expense. The method proposed is as follows:

A small water supply is to be obtained at considerable head over the reservoir site, either by diverting the stream at a distance above the reservoir or by storing waters in a small reservoir on the stream or some of its tributaries and carrying them in pipes or flumes above the upper edge of the reservoir to the vicinity of the dam. At points along the side of the reservoir which are topographically favorable, preferably upon ridges jutting out into the lake, hydraulic giants are to be provided, to act under the head of water furnished by the pipe line. Large sluiceways are to be provided near the dam, and at such times as the reservoir happens to be empty these sluiceways are to be opened to their full capacity and the deposited material hydraulicked out, as in hydraulic mining. The material, being mostly fine and freshly deposited, would wash easily and rapidly and be carried by the stream out of the reservoir through the sluice gates. This water need not be wasted, but could be diverted below for purposes of irrigation. It is not denied that such works and such methods would be expensive, but, on the other hand, their effectiveness is unquestionable, and it is believed to be by far the most feasible method yet proposed for cleaning out a large reservoir. The tendency of an economical use of this method would be to keep the reservoir open in its lower part, where it is deepest, and allow the shallow portions along the edges and at the upper end to remain filled. This would contract the relative area of water surface and diminish evaporation, which would in a measure compensate for the destruction of storage capacity.

The use of the three methods, first, the employment of one or more large scouring sluices, after the manner of the old Spanish reservoirs; second, the enlargement of the reservoir to the practicable limit; and, third, the construction of works and the adoption of operations like those above described, would in many cases insure the perpetuity of

storage reservoirs in this country within practicable limits of expense. Certain it is that some efficient method or methods for this purpose must be employed or the extension of irrigation in any great degree in southern Arizona by means of storage is impossible.

The problem just discussed suggests the advisability, where feasible, of constructing storage reservoirs in side canyons or other basins having no considerable natural drainage tributary to them, the water being carried through artificial conduits from the streams whose waters it is desired to store. Where this can be done the danger of filling the reservoir with silt can be easily averted. Sand boxes can be constructed along a conduit and easily operated in such manner as to effectually clear the waters of their load of solid matter.

Aside from the scarcity of natural sites of this character, their efficiency is limited by a fact more strongly emphasized in this than in most countries, that the surplus waters are discharged in sudden floods of enormous volume, and in order to impound them or any considerable percentage of them by this method, not only must strong diversion works be provided for diverting them, but a conduit must be constructed of enormous capacity. If this conduit must be of considerable length or in very rough country—and both conditions usually obtain—the project is defeated by that great bugbear of irrigation possibilities previously referred to—the cost.

In respect to the existence of good natural reservoir sites upon streams carrying the bulk of its surplus waters, southern Arizona is particularly fortunate. The information upon this point, however, is far from complete, and the subject deserves careful expert investigation.

EVAPORATION.

As previously suggested, one of the most serious obstacles to the extension of irrigation in Arizona by means of storage is the high rate of evaporation, which often exceeds 100 inches in depth in a single year.

A compilation of evaporation results acquired by the Irrigation Survey is given in the Eleventh Annual Report of the Geological Survey, Part II, Irrigation, page 34.

It has been proposed to lessen evaporation from reservoirs by the cultivation of aquatic plants, whose leaves are intended to cover the surface and partially shade the water. This plan was suggested by Captain Glassford in Irrigation and Water Storage in the Arid Regions, page 307.[1] It is hardly probable that this method can be very effective, from the fact that such part of the leaves as are above water will probably transpire more or less moisture themselves, and such parts as are covered with a film of water of course can not check

[1] Fifty-first Congress, second session, Ex. Doc. No. 287, Irrigation and Water Storage in the Arid Regions, a report on the climatology of the arid regions of the United States with reference to irrigation. By Gen. A. W. Greely.

evaporation in any degree. A test of a similar method of checking evaporation was made by Prof. Edward M. Boggs, irrigation engineer and meteorologist of the Arizona Agricultural Experiment Station, the result of which is given by him in Bulletin No. 20, on Arizona Weather, page 7:

A second tank, an exact duplicate of the first, placed by its side, and provided with a similar gauge, was planted with water lilies of the genus *Nymphæ*. Measurements were commenced in this tank in September, 1892, when the leaves well covered the surface of the water. They were continued until April, 1894, when the gauge was needed for another use. A comparison of the results is shown by parallel columns in Table IV. It will be seen that the monthly totals of the two tanks are in substantial agreement. The differences are usually small. The excess changes so often from one tank to the other as to lead to the conclusion that differences are due to accumulations of errors incident to observation. But it is not easy to apply this explanation to the difference of 0.75 inch in favor of the lily tank occurring in June, 1893. However, the idea that the leaf covering has diminished the evaporation to any considerable extent is dispelled by the fact that for the eighteen months of the record the difference amounts to 1.52 inches only, a divergence of about 1 per cent.

Another device is here proposed which may be worthy of consideration, and which it is hoped may receive tests similar to those conducted by Professor Boggs. It is proposed to cover the surface of the reservoir with a film of crude petroleum, which will form a more or less coherent sheet of gum upon the surface and prevent the contact of air with the water as long as the surface of the reservoir is still and placid. The tendency of oil to diminish motion of water in waves and riffles is well known, and this project might prove more or less effective at such times as the winds are not too violent or constant. This suggestion is made for what it is worth, in the hope of inducing experiments to test its value. It must be admitted, however, that the prospect is meager for materially reducing the ravages of evaporation from reservoirs in this climate, and all plans and estimates should take them into account to the fullest extent.

MOUNTAIN RESERVOIRS.

It is eminently advisable in such a climate as that of Arizona to store waters for irrigation as far as practicable near their source, in order to obviate the enormous loss through evaporation when flowing for long distances through the sandy beds of streams.

It is often erroneously assumed that the run-off of a district is nearly proportioned to its area. In this arid region the mean discharge of the large streams is, owing to evaporation, often more nearly in inverse proportion to their catchment areas. Thus the Gila River at Yuma has a smaller discharge than at the mouth of Salt River, where its catchment area is far less. The Santa Cruz River, at the point where it leaves the mountains, discharges annually large quantities of water, which become progressively less, until well out into the

desert the river is practically lost, and its discharge is zero. The same is true in a greater or less degree of nearly all the important drainage lines in the southern part of the entire arid region. Added to this is the fact that in the low, hot deserts the evaporation is usually so great as to make very serious ravages into the stored volume of water after the rains have ceased, thus materially reducing the supply available for irrigation.

The waters from a reservoir situated within a broad valley or open country must usually be conducted in broad channels constructed on light grades through sand or loam where the loss from seepage and evaporation will approximate a maximum; while from a mountain reservoir it is usually possible to give delivery canals heavy grades and high velocities, reducing seepage and evaporation to a minimum; and, with plenty of grade to spare, natural drainage lines may be utilized to a great extent. The seepage from high-level canals often reappears at lower levels and is not entirely lost. Furthermore, water stored in the mountains may usually be made to furnish a large amount of power that will in the future be very valuable, without in the least affecting its availability for irrigation. It may be laid down as an almost general rule that where there is a choice it is far better for the future of the arid region that water be stored in or near the mountains than on desert plains, even when the cost of such mountain storage is much greater than the same capacity at lower levels.

The reservoir sites already described on New River, Rio Verde, Gila and Salt rivers, Hassayampa, Queen, and Cave creeks, which are contemplated in the plans of existing companies, are doubtless the best that can be utilized on those streams, and are usually as great and in some cases greater in capacity than required for the economical conservation of the waters yielded by the drainage area tributary to them, exclusive of the great unusual floods which, as previously pointed out, it is neither practicable nor desirable to impound. On the drainage of the Gila proper, however, it is not improbable that undiscovered reservoirs exist in the mountains near the head waters of the Santa Cruz, San Pedro, San Francisco, and Gila rivers; Eagle, San Carlos, and Blue creeks, and other tributaries in the mountainous regions, where waters can be more economically stored than at The Buttes. When all such reservoirs are constructed and fully utilized, and the ordinary spring and summer flow of the river entirely diverted for irrigation in the neighborhood of Solomonville and Fort Thomas, the reservoir at The Buttes may be relied upon to impound the balance of the run-off tributary to its drainage, with the exception of the unusual floods referred to. This reservoir is admirably located for the purposes above outlined, being of large capacity and, situated at the point where the river finally leaves the mountainous region, intercepting nearly all the mountain drainage

yielding the largest percentage of run-off, and yet of sufficient elevation to command all the irrigable land adjacent to the middle and lower portions of the river.

When all such sites are utilized there will still be a large area of excellent unwatered lands in the valleys of Arizona and a large amount of surplus flood waters, which, for reasons outlined on page 79, it is not practicable to store in the reservoirs in the mountains. Though these reservoirs include in their catchment the greater portion of the best drainage area of this basin, large areas of foothills, plains, and rocky ridges will still remain which are subject to occasional cloudbursts and yield in the aggregate a large run-off. A part of such waters, as well as such part of the seepage from canals and irrigated fields as finds its way back into the stream, can be impounded by the construction of a large reservoir on the lower Gila, as described on page 76. Whether it would be sufficient to utilize the water available for storage after the upper sites in this basin have been brought into use can not, of course, be known at present. Certain it is that no rights to flood waters should be acquired by such a reservoir to the prejudice of those in the mountain regions, where the water can be so much more economically impounded and applied, and in the absence of laws controlling this matter it is not to be regretted, but is rather a subject for congratulation, that this project has not been carried to completion; and it is to be hoped, for the sake of the future of irrigation in Arizona, that it will not again be revived until at least the best of the reservoir sites hereinbefore described have been constructed or some legal provision has been made to secure their full utilization.

UNDERGROUND WATERS.

The possibilities of irrigation by the development of percolating waters deserves mention. There is in Salt River Valley at present a large quantity of water in the gravels underlying the valley. The well employed to furnish the greater part of the domestic supply of water for the city of Phœnix is 35 feet in depth and 8 feet in diameter. It normally contains a depth of 18 feet of water. The walls are of cement, so that water can enter only at the bottom. Two Dean pumps, each of 840 gallons per minute capacity, are used to raise the water into the stand pipe. Both pumps usually run at nearly full capacity in July and August, and have raised 33,000,000 gallons per month. The discharge has sometimes exceeded 1,400 gallons per minute, which would lower the water in the well about 6 feet, but when the pumps are stopped the water recovers its level in a few minutes. A well was dug into the gravel in the vicinity of Mesa, and a centrifugal pump of about 1,200 gallons per minute capacity was used to keep the water down and permit the progress of the work. The

ingress of water became so great as to be beyond the capacity of the pump, and work was stopped for that reason.

This large quantity of underground water is doubtless due to the excessive application of water, as previously described in this report, through the months of April and May, while the water in Salt River is abundant, and irrigators are attempting to "soak up" the land preparatory to the low-water season, when the competition for water rights becomes severe. If in future this excessive supply during the spring months is stored in great reservoirs, as is proposed by the projects now contemplated, the "underflow" will be greatly reduced, because so great an excess of water will no longer be applied to the fields. Some water will always escape from the fields into the subsoil, and canals and ditches will also lose a portion of their supply by seepage, which will be caught by the underflow. This source of supply, while for these reasons somewhat uncertain at present, is important in the future development of the valley.

Measurements were made in the month of June, 1896, by Mr. Cyrus C. Babb, of Salt River above the head of the Arizona Canal, of the amount of water taken out by each canal, and the amount remaining in the river below its head. These measurements proved that a considerable quantity of water is returned by seepage to the river bed, which was taken out for irrigation lower down. In one case the increase was 80 second-feet in 7 miles, as previously stated. Undoubtedly the amount lost by evaporation of these return waters from the river bed and the adjacent soils was much greater. While it is a gratification to know that some part of the surplus waters applied to the land returns to the river and can be used again, still this fact affords no excuse for such use, and should not be allowed to weigh in favor of its continuance.

In some other parts of the Territory are found underground waters in greater or less abundance, which may in some cases be profitably developed by pumping or otherwise for irrigation purposes. This is true at least in the country which receives the lost waters of the Santa Cruz and some other streams which have ordinarily little or no surface indications, but still discharge more or less water through a pervious subsoil. Water may be obtained in abundance a short distance beneath the surface along the valley of the Gila River, in the Pima Reservation.[1] Mr. Albert F. Colton has collected a quantity of data relating to wells in the Casa Grande Valley, some of which have quite a considerable flow and vary in depth from 20 to 100 feet. In other parts of the Territory wells have been sunk to depths greatly exceeding 100 feet without striking water. The information collected by the Geological Survey, together with that gathered by Mr. Colton, so

[1] Irrigation Investigation for Pima Reservation. Senate Doc. No. 27, Fifty-fourth Congress, second session.

far as relates to Maricopa and Pinal counties, is shown in the following tables:

Wells of Pinal County.

No.	Post-office.	Owner of well.	Location.			Year completed.	Diameter.	Depth of well.	Depth of water.	Cost of—	
			T.	R.	S.					Well.	Machinery.
							Ft. in.	*Feet.*	*Feet.*		
1	Arizola	Geo. W. Sanders	6	6	22	1892	4 0	40	3	$100	$13
2	do	Peter H. Loss	6	7	19	1893	4 0	44	6	35	
3	do	H. J. Cleveland	6	7	19		0 6				
4	do	Fred Weaver	6	7	32	1896	4 0	52	2		
5	do	—— Cooley	7	7	5	1895	4 0	53	3		
6	do	M. R. Mann	7	6	1	1894	3½ 0	54	2	54	
7	do	E. Hadley	6	6	34	1892	4 0	50	5		
8	Casa Grande	R. B. Dennis	6	6	20	1896	5 0	45	2		
9	do	Andrew Soundburg.	6	7	36		4 0	49	3		
10	do	L. S. English	6	5	23	1892	4 0	56	5		
11	do	F. G. Logan	6	6	32		0 6	75	30		
12	do	S. P. R. R.	6	6	29		8 0	56	8		
13	Dudleyville	George Scott	4		25	1885	4½ 0	14	2	5	15
14	do	O. H. Swingle	6	16	20	1878	4 0	21	6	25	40
15	Florence	A. T. Colton	5	9	35	1888	4 0	45	1	56	
16	do	Whitney	5	9	10	1891	4 0	70	2		
17	do	Christopher Salmon.	5	7	25	1890	3 0	30	2	40	100
18	do	T. F. Marquand	5	7	13	1895	12 0	23	7½		
19	do	L. E. Graham	5	8	24	1891	6 0	56	6		150
20	do	J. M. Hurley	5	9	32	1891	4 0	102	31		
21	do	James F. Pry	5	8	27	1896	3 8	39.3	1.7	10	
22	do	Wm. H. Graham	5	8	28	1893	4 0	32	4		
23	do	F. E. Carpenter	5	8	35		4 0				
24	do	—— Morrell	5	8	26		3½ 0	44	4		
25	do	Daniel Bingham	5	8	26		4 0	51	2		
26	do	Shields & Price	5	8	24		3 0	66	5	66	300
27	do	Peter R. Brady	4		34	1884	4 0	27	2	90	
28	do	Abandoned	3	10	35		10 0	100	0		0
29	do	Thos. Buchanan	1	8		1885	0 5	232	24		
30	do	Whitlow Bros	2	10	1	1883	0 6	126	106	500	100
31	do	R. H. Martin	3	10	5	1883	0 6	413	0	1,000	
32	do	Harrington	2	7		1892	0 4	160	5		
33	do	Lew Baley	2	10	14	1888	0 6	180	0		
34	do	Mexican	1	10	34	1882	0 4	58	0		
35	do	Barmodath	1	10		1883	0 4	158	0		
36	do	Bark & Creswel	1	10		1879	0 6	18	9		
37	Kenilworth	W. J. L. Baron	5	8	25	1892	4 0	65	5½	65	
38	Maricopa	S. P. R. R.	4	3	17	1885	16 0	34	5		
39	Sacaton	Wilson	6	5	24		4 0	42	2½		
40	do	W. J. Stulz	6	7	27	1895	3 0	52	3	50	
41	do	U. S. Indian agent	4	6			11 0	26½	8½		

Wells of Maricopa County.

No.	Post-office.	Owner of well.	Location.			Year completed.	Diameter.	Depth of well.	Depth of water.	Cost of—	
			T.	R.	S.					Well.	Machinery.
							Ft. in.	*Feet.*	*Feet.*		
42	Phoenix	E. F. Kellun	1	1	6	.....	0 7	554	.....	$5,000	.....
43	.....do	Frank A. Phillip	1	2	27	1892	14 0	26	14	300	$2,700
44	.....do	Phœnix Waterworks.	1	3	5	1889	8 0	35	17	5,000	10,000
45	Tempe	C. G. Jones	1	4	13	1889	4½ 0	20	12	.....	.....
46	Mesa	Wm. Standage	1	5	20	1895	5 0	42	4	80	.....

No. 1.—Dug well; depth of water does not vary; it can not be easily lowered; flow has not diminished; water, soft; raised by bucket and used for domestic purposes; elevation of surface, 1,412. Strata passed through: Sandy soil, 11.5 feet; volcanic ash, 3 feet; hard whitish rock, 2 feet; sand and small gravel, 8.5 feet; wash gravel, 3 feet; hard whitish rock, 1 foot; gravel, 2 feet; hard rock of a water-line formation, 9.5 feet.

No. 2.—Dug well; depth of water does not vary, nor is it easily lowered; flow remained stationary; water rose 4 feet when struck; water, soft; raised by pump and used for domestic purposes; elevation of surface, 1,448 feet. Strata passed through: Clay soil, 6 feet; gravel, 8 feet; sand, 28 feet; rock of a water formation, 2 feet.

No. 3.—Bored well; elevation of surface, 1,452 feet.

No. 4.—Dug well; depth does not vary; is not easily lowered; quality of water, soft; raised by bucket and used for domestic purposes; elevation of surface, 1,458 feet. Strata passed through Clayish soil; last foot lime as water formation.

No. 5.—Dug well; depth does not vary during year; quality of water, soft; water raised by buckets and used for domestic purposes; elevation of surface, 1,460 feet. Strata passed through: Same as No. 4.

No. 6.—Dug well; depth does not vary during year; is not easily lowered; quality of water, soft; raised by bucket and used for domestic purposes; elevation of surface, 1,450 feet. Strata passed through: Clay, with streaks of gravel; bottom in sand.

No. 7.—Dug well; depth does not vary during year; is not easily lowered; quality of water, hard; water raised by buckets and used for domestic purposes; elevation of surface, 1,438 feet.

No. 8.—Dug well; water easily lowered; quality of water, soft; raised by buckets and used for domestic purposes; elevation of surface, 1,393 feet. Strata passed through: Clay soil, 12 feet; cement, 14 feet; sand, 12 feet; then clay to water.

No. 9.—Dug well; quality, soft; raised by bucket; used for house and stock; elevation of surface, 1,454 feet. Strata passed through: Sandy soil; bottom in sound rock.

No. 10.—Dug well; depth of water does not vary during year; is not easily lowered; flow has increased; quality of water, salt at first, hard now; raised by buckets and used for domestic purposes; elevation of surface, 1,375 feet. Strata passed through: Gravelly soil; water in gravel.

No. 11.—Bored well; depth of water does not vary during year; is not easily lowered; water, alkaline; raised by windmill; elevation of surface, 1,405 feet.

No. 12.—Water not easily lowered; it rose when struck; flow increased; water, hard; raised by pump; flow, 10,000 gallons per hour; elevation of surface, 1,395 feet. Strata at bottom: White sand.

No. 13.—Dug well; depth varies with height of river; can not be easily lowered; quality, a little alkaline; raised by pump; used for domestic purposes. Strata passed through: Alluvial soil, with sand at water level.

No. 14.—Dug well; depth does not vary during year; can not be easily lowered; water, hard; pumped and used for domestic purposes. Clay strata passed through.

No. 15.—Dug well; depth at first, 33 feet; water at 31 feet; sunk 1.5 feet each year; present depth, 45 feet, and 1 foot water; is easily lowered; flow diminished; elevation of surface, 1,488 feet. Sandy clay soil.

No: 16.—Dug well; depth varies during year; water, hard.

No. 17.—Dug well; depth does not vary; is not easily lowered; rose one-half foot when struck; quality, soft; used for house and stock; elevation of surface, 1,398 feet. Sandy soil; bottom in sand.

No. 18.—Dug well; depth does not vary during year; lowers about 3 feet and no more; raised by gang pump and horsepower; flow, 6,600 gallons per hour; used for irrigation; elevation of surface, 1,380 feet. Sandy soil for 13 feet; 2.5 feet clay; then water in sand.

No. 19.—Dug well; commences to lower in November and rise in April; variation about 1 foot; not easily lowered; quality, soft; raised by horsepower; waters 120 head of stock; elevation of surface, 1,455 feet; gravelly soil; bottom in water formation.

No. 20.—Dug well; depth does not vary; is not easily lowered; quality, medium; raised by pump; used for domestic purposes; elevation of surface, 1,505 feet; usual water formation of rock at bottom.

No. 21.—Dug well; quality, soft; raised by bucket; used for domestic purposes; elevation of surface, 1,440 feet; sandy soil on top water rock.

No. 22.—Dug well; water rises last of June, falls in December; not easily lowered; quality, soft, but getting hard; raised by pump; waters 20 head of hogs, 70 head of stock, 120 trees; elevation of surface, 1,416 feet; soil, sand and clay, with strata of hardpan at bottom, blue clay; main stream comes in from southeast.

No. 23.—Quality, soft; elevation of surface, 1,441 feet; same rock bottom.

No. 24.—Dug well; quality, salt; elevation of surface, 1,439 feet; sandy soil; bottom below water lime.

No. 25.—Dug well; quality, soft; elevation of surface, 1,450 feet; sand strata.

No. 26.—Dug well; depth varies during year; not easily lowered; quality, hard; raised by steam pump; elevation of surface, 1,467 feet; at 3 feet struck coarse gravel, lasting 20 feet; bottom in water lime.

No. 27.—Dug well; cased with redwood; lowers in summer; easily lowered; quality, soft and pure; soil, 11 feet alluvium, balance quicksand.

No. 29.—Dug well; size, 4 feet at top, 6 feet at bottom; level lowers some in summer; quality, soft; raised by steam pump, 1,000 gallons in twenty-four hours; used for stock, garden, and traveling public; strata, clay, sand, and small gravel, bottom in coarse gravel.

No. 30.—Drilled well; depth does not vary; can not be lowered with horsepower pump; used for stock; strata, limestone.

No. 32.—Dug well; depth lowers in summer; raised by horsepower and barrel; can be pumped dry in five hours; used for stock and by the public.

No. 33.—Drilled well; dry; 3 miles southwest of Whitlow's ranch; between this well and Florence are three other dry wells, with depths of 150 feet each.

No. 34.—Well sunk in Queen Creek wash, 2½ miles below Whitlow's ranch; no water found.

No. 36.—Well at Goldfield; more water in well in winter; can be easily lowered; raised by hand pump; used for stock.

No. 37.—Dug well; level rises in April, falls last of July; is easily lowered; flow has increased; quality, soft at first, now medium; raised by buckets, and waters 100 head of stock and 30 trees; elevation of surface, 1,465 feet; gravelly soil with streaks of limestone.

No. 38.—Dug well; not easily lowered; water soft; raised by steam pump; discharge, 10,000 gallons per hour; elevation of surface, 1,170 feet; gravelly soil.

No. 39.—Dug well; elevation of surface, 1,380 feet; bottom in gravel.

No. 40.—Dug well; depth does not vary during year; can be lowered by two buckets; water soft, raised by buckets, and used for domestic purposes; elevation of surface, 1,450 feet; sandy soil; water in a soft sandstone.

No. 41.—Dug well; capacity tested by 6-inch centrifugal pump giving one-tenth of a cubic foot per second, or 8,640 cubic feet per day; percolating area, 242 square feet, indicating a yield of 36 cubic feet per day for each square foot of surface. This surface is in a very hard clay, which has stood eight years without walling and still shows marks of the pick used in digging; water used for mill and domestic purposes; raised by steam pump.

No. 42.—Bored and drilled well; 18 feet to surface water; slight flow at 382 feet; not easily lowered; used for irrigation; alluvial soil 15 feet, hardpan 10 feet, alternate gravel beds 150 feet, sand, cement, etc.

No. 43.—Dug well; depth fluctuates about 30 inches during year; can not be easily lowered; quality, soft; raised by steam pump; discharge, 2 second-feet, and irrigates 320 acres.

No. 44.—Dug well; level not easily lowered; quality, hard; water raised by pumping; discharge, 2,500,000 gallons per day; supplies water to city of Phœnix; level steadily risen during past ten years; first 16 feet alluvial soil, balance bowlders and coarse gravel.

No. 45.—Dug well; cased for 6 feet; level varies 4 feet during year; can be easily lowered; quality, soft; raised with bucket, and used for domestic purposes; strata, soil for about 14 feet, hardpan of cement and rocks, gravel.

No. 46.—Dug well; walled with brick; depth varies during year; not easily lowered; quality, soft.

A scientific investigation of further possibilities is very important, both to develop resources along this line and to obviate further loss from unsuccessful attempts of this character. The irrigation possibilities from underground development are undoubtedly important, but it is not intended here to emphasize this fact, for the popu-

lar mind is already filled with very exaggerated ideas of such possibilities. Extravagant estimates of the quantity of "underflow" are rife on all hands, and it is recognized as an important though thankless duty to disabuse the public mind of such erroneous ideas so far as possible. One phase of this general impression is the opinion that the dry streams which abound in the valleys of Arizona must have a large underflow because the same streams carry considerable water farther up in the mountains. It seems to be forgotten that the potential evaporation in the valleys of Arizona ranges, according to locality and season, from 5 to 10 feet in depth on the entire area exposed to such evaporation.

It is the common assumption that evaporation is much higher from a water surface than from a saturated soil. The actual data on this point are very meager, but so far as observations have been taken they seem to indicate that evaporation is greater from saturated sands than from the surface of a deep body of water, even though such sands may appear dry on the surface. The reason for this may be found in the fact that the temperature of such sands rises much higher under the action of the sun than that of a large body of water; also, that for a considerable distance below the surface the particles of sand or of soil are kept moist by the action of surface tension and capillarity for a considerable distance above the point where all the voids in the sand are filled with water. By this means a far greater area of moist surface is exposed to the action of the dry air than is the case with a smooth sheet of water.

But whatever the reason, and whatever the exact ratio the evaporation from a sand bed bears to that of a body of water, we do know that it is very great, and that if the precipitation of the entire Territory of Arizona were so distributed as to give the potential evaporation of the climate full play, the evaporation would, even in the very wettest years, absorb the entire rainfall, and the run-off would at all times be absolutely zero. That the streams do yield a considerable quantity of run-off in the aggregate is due to the fact that precipitation is largely in excess of evaporation at certain times and in certain places, while at other times and in other places no moisture at all is exposed to the evaporating influence.

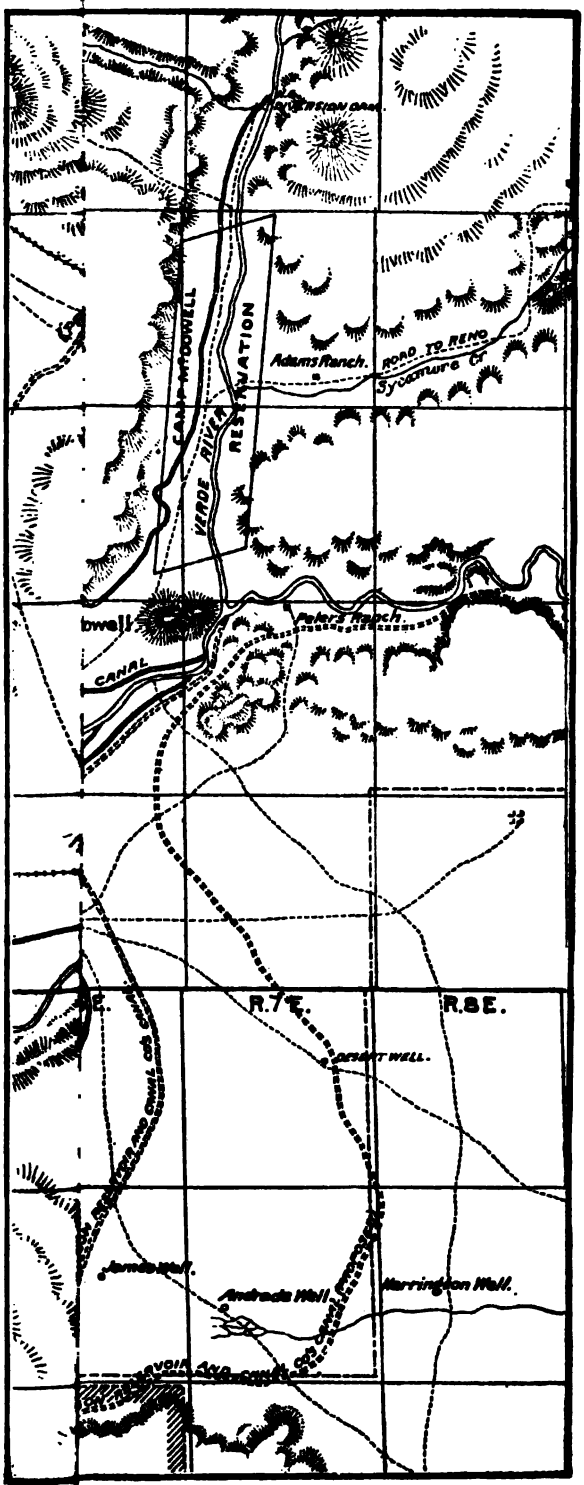
The above-recited facts are abundantly sufficient to account for the phenomena of many streams having a considerable discharge near their source in mountain regions and being ordinarily dry in valley regions, by the evaporation of the water from their sandy beds, without introducing the hypothesis of a large underflow. The Agua Fria is a typical stream in point. There are parts of its upper course in which it is ordinarily a very considerable stream and is never dry; near its mouth it is ordinarily entirely dry and carries water only in seasons of excessive rainfall. The idea seems to have been at one time prevalent that this stream carried a large amount of the

so-called "underflow," but the construction of the dam of the Agua Fria Water and Land Company, a short distance below Frog Tanks, which was carried down 40 feet through the sands to bed rock, made little or no perceptible increase in the permanent volume of water flowing at that point. A measurement was made of the water flowing through the sluiceway of the dam in April, 1896, and this showed a discharge of only 3.75 cubic feet per second, which is said to have been about the ordinary flow previous to the construction of the dam. Another measurement made the same day about a mile above this point showed a discharge of about 3 cubic feet per second. The difference between these measurements may perhaps indicate the increase in the stream due to the development of the underflow, though even this is by no means certain. Even if the entire discharge of the stream were considered as developed from the underflow, its volume is nowhere near commensurate with the cost of development. While the experience in this case is of course not conclusive with respect to all other streams, it is an emphatic refutation of the popular theory that such water as falls in rain must be found either flowing in the surface streams or underground. Attempts at extensive underground development should in all cases be preceded either by careful and judicious experiments or thorough scientific investigation.

The development of underground waters by means of pumps is greatly hampered by the scarcity and cost of suitable power. In some parts of the Territory firewood is at present abundant and cheap, but it is of slow growth, and if extensively employed in irrigation would in time become exhausted. The price of coal is prohibitory for any such purpose on a large scale in any part of the Territory, as is also that of petroleum, gasoline, or any other importable fuel. The time may come when some of the many available water powers in the foothills will be harnessed for the generation of electricity, to be transmitted to proper points and used for pumping water for irrigation, but these schemes can hardly be considered at present within the realm of practical consideration. A few attempts have been made to harness the winds to this work, but this motive power, always fickle and unreliable, seems to be especially so in these valleys; long periods of calm are said to occur during the months when water is most needed, and it is usually considered necessary to reenforce such plants with steam or other motive power. Some development, however, may be expected from nearly all the methods above mentioned, but for a long time to come they must necessarily be on a small scale and usually for individual purposes.

SUMMARY.

It may be in order here to point out some of the difficulties under which irrigation has heretofore labored, and to suggest means for obviating them in future. A glance at the map of Salt River Valley


CAMP McDOWELL
VERDE RIVER RESERVATION
Adams Ranch.
ROAD TO RENO
Sycamore Cr.
Peter's Ranch.
CANAL
R.7E.
R.8E.
DESERT WELL.
Andrade Well
Harrington Well.

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(Pl. XXX) will show at once that there has been an enormous waste of energy in the construction of numerous and parallel canals with conflicting claims and interests. On the north side of the river are the Farmers', Salt River, Maricopa, Grand, and Arizona canals, to be paralleled by the partly constructed Rio Verde Canal. All of the land under the Arizona Canal could be watered much more cheaply and with far greater economy of water from the Arizona Canal and its laterals. Most of the labor and capital expended in the construction of the others has been worse than wasted. So long as they are used in competition with a larger canal, acrimonious contests over water rights are the inevitable result, and when all concentrate under one management the competition for water rights is transferred from companies to individuals, and as long as the smaller canals remain in use they are a fruitful source of waste of valuable water. On the south side of the river the condition is, if possible, still worse. The Broadway and San Francisco ditches, and Tempe, Utah, Mesa, and Highland canals will be paralleled by a higher canal proposed by the Hudson Reservoir and Canal Company. They might be advantageously superseded by a single large, high-line canal, which would be far more economical of water, and all the labor and expense of the smaller canals would thereby be obviated. The greatest evil of the system, or rather lack of system, heretofore followed in the development of irrigation along Salt River, however, is the growth of conflicting claims to water. This has always been productive of vindictive and expensive litigation. Large areas of land have been brought under cultivation having no adequate water right, and crops have been dried up and labor wasted, and some areas abandoned, for lack of water for irrigation. This evil in this particular valley, so far as present conditions are concerned, may perhaps be largely remedied by the construction of storage works upon the Verde and Salt rivers; but unless means are employed to prevent it the same condition will again arise when the limit of irrigation is reached under the storage systems proposed.

Whatever claims are made to the contrary, it is a fact that the area of land to be irrigated in this portion of the Territory is much larger than can be served by any possible water supply that can be made available for such irrigation. Neither Arizona nor Salt River Valley is any exception in this regard to the rest of the arid region, but in Arizona and New Mexico the land and water are both still under the jurisdiction of the United States Government, and steps should at once be taken to determine where and to what extent the water resources can be most economically developed, and no irrigable land should pass out of the hands of the Government for irrigation purposes except such areas as it may be possible to irrigate. Persons should not be allowed to obtain possession of the lands to be irrigated except upon terms involving actual irrigation and cultivation. The

absurdity and wastefulness of the contrary policy are strikingly illustrated by a study of the map of the irrigated areas under the Florence Canal. More than a hundred thousand acres of irrigable land might be conveniently served by this canal if it had a sufficient quantity of water. There are, in fact, about 6,500 acres watered from it, very little of which lies near the canal, and most of which is in small isolated tracts. To water such tracts in such a manner requires not only a large amount of construction upon laterals, which under any rational system would be unnecessary, but it also involves an enormous loss of water through evaporation and seepage from the long laterals required to conduct the water to the small scattered patches of cultivated ground. The water flowing through the Florence Canal during the year 1896 was more than treble that which would be required to mature the crops grown in that year had it been economically distributed and applied.

The following summary of the various conditions and possibilities regarding the irrigated areas of the Gila River and Salt River valleys must be taken with a large allowance for error both regarding existing conditions and future possibilities. It is, however, of some value and interest as representing in round numbers the results of the best data at present available to the public.

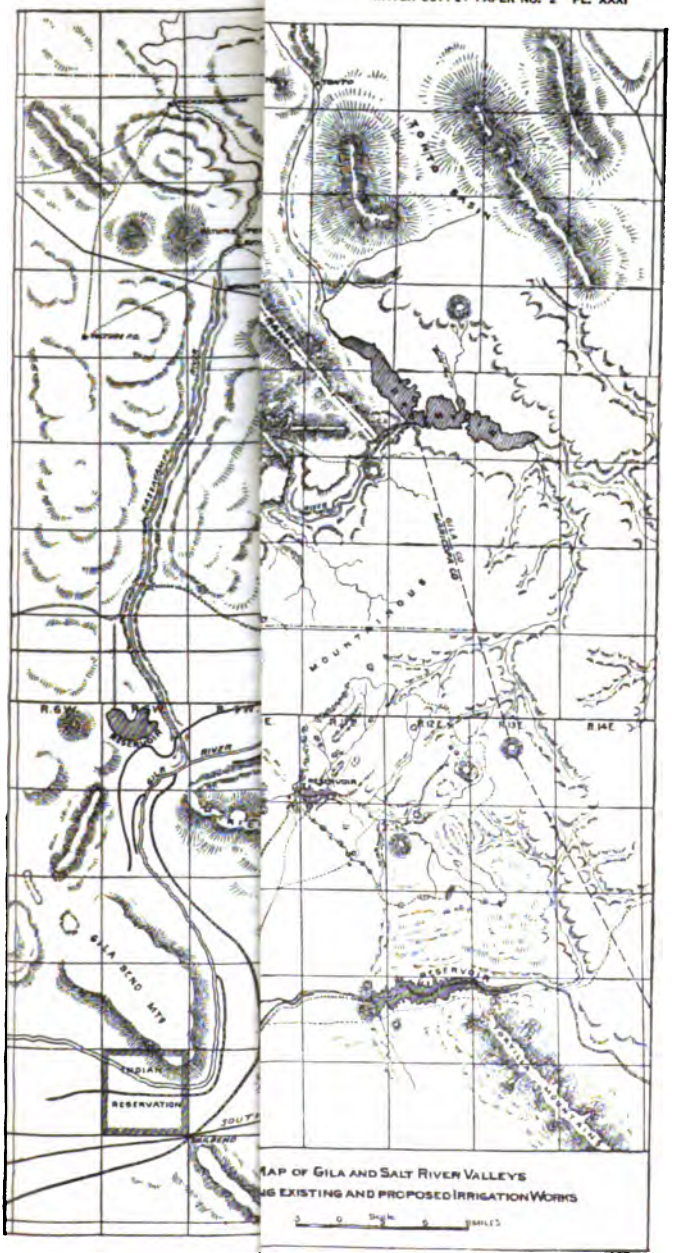
Summary of irrigation in Gila River and Salt River valleys.

	Acres.
Irrigated area in Cochise County	3,000
Irrigated area in Gila County	1,000
Irrigated area in Graham County	10,000
Irrigated area in Maricopa County	80,000
Irrigated area in Pima County	4,000
Irrigated area in Pinal County	7,000
Irrigated area in Yuma County	1,000
Total irrigated area	106,000

Additions may be made to the above area as follows:

	Acres.
Rio Verde Canal project, including New River Reservoir	150,000
Tonto Basin project	300,000
Agua Fria project, both reservoirs	80,000
Cave Creek project	10,000
Queen Creek project	5,000
Walnut Grove project	5,000
The Buttes Reservoir	100,000
Oatman Flat Reservoir	50,000
Various small reservoirs on tributaries of the Gila	50,000
Underground developments	20,000
Total	770,000
Already irrigated	106,000
Grand total	876,000

It is believed that these estimates are generous and that it will be very many years before the above figures are approached in actual practice. Of course other possibilities exist in Arizona from the use of the waters of the Colorado and its tributaries other than the Gila system. This estimate includes only the Gila system, and though the above figures are only rough estimates, they are suggestive of the importance to the future of Arizona of some comprehensive system of irrigation administration based upon principles of broad economy, and especially of the necessity of an exhaustive investigation of the water resources and of the most efficient means of utilizing them.



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DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 3

SEWAGE IRRIGATION.—RAFTER

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

IRRIGATION REPORTS.

The following list contains the titles and brief descriptions of the principal reports relating to water supply and irrigation prepared by the United States Geological Survey since 1890:

1890.

First Annual Report of the United States Irrigation Survey, 1890, octavo, 123 pp.

Printed as Part II, Irrigation, of the Tenth Annual Report of the United States Geological Survey, 1888-89. Contains a statement of the origin of the Irrigation Survey, a preliminary report on the organization and prosecution of the survey of the arid lands for purposes of irrigation, and report of work done during 1890.

1891.

Second Annual Report of the United States Irrigation Survey, 1891, octavo, 395 pp.

Published as Part II, Irrigation, of the Eleventh Annual Report of the United States Geological Survey, 1889-90. Contains a description of the hydrography of the arid region and of the engineering operations carried on by the Irrigation Survey during 1890; also the statement of the Director of the Survey to the House Committee on Irrigation, and other papers, including a bibliography of irrigation literature. Illustrated by 29 plates and 4 figures.

Third Annual Report of the United States Irrigation Survey, 1891, octavo, 576 pp.

Printed as Part II of the Twelfth Annual Report of the United States Geological Survey, 1890-91. Contains a report upon the location and survey of reservoir sites during the fiscal year ending June 30, 1891, by A. H. Thompson; "Hydrography of the arid regions," by F. H. Newell; "Irrigation in India," by Herbert M. Wilson. Illustrated by 93 plates and 199 figures.

Bulletins of the Eleventh Census of the United States upon irrigation, prepared by F. H. Newell, quarto.

No. 35, Irrigation in Arizona; No. 60, Irrigation in New Mexico; No. 85, Irrigation in Utah; No. 107, Irrigation in Wyoming; No. 153, Irrigation in Montana; No. 157, Irrigation in Idaho; No. 163, Irrigation in Nevada; No. 178, Irrigation in Oregon; No. 193, Artesian wells for irrigation; No. 198, Irrigation in Washington.

1892.

Irrigation of western United States, by F. H. Newell; extra census bulletin No. 23, September 9, 1892, quarto, 22 pp.

Contains tabulations showing the total number, average size, etc., of irrigated holdings, the total area and average size of irrigated farms in the subhumid regions, the percentage of number of farms irrigated, character of crops, value of irrigated lands, the average cost of irrigation, the investment and profits, together with a resume of the water supply and a description of irrigation by artesian wells. Illustrated by colored maps showing the location and relative extent of the irrigated areas.

1893.

Thirteenth Annual Report of the United States Geological Survey, 1891-92, Part III, Irrigation, 1893, octavo, 486 pp.

Consists of three papers: Water supply for irrigation, by F. H. Newell; American engineering and engineering results of the Irrigation Survey, by Herbert M. Wilson; Construction of topographic maps and selection and survey of reservoir sites, by A. H. Thompson. Illustrated by 77 plates and 119 figures.

A geological reconnoissance in central Washington, by Israel Cook Russell, 1893, octavo, 108 pp., 15 plates. Bulletin No. 108 of the United States Geological Survey; price, 15 cents.

Contains a description of the examination of the geologic structure in and adjacent to the drainage basin of Yakima River and the great plains of the Columbia to the east of this area, with special reference to the occurrence of artesian waters.

(Continued on third page of cover.)

DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 3

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

SEWAGE IRRIGATION

BY

GEORGE W. RAFTER

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

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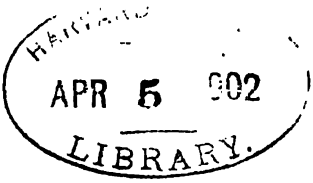

Chas Moore

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, February 4, 1897.

SIR: I have the honor to transmit herewith a paper entitled "Sewage Irrigation," by George W. Rafter, and to recommend that it be published as the third number of the series of papers upon water supply and irrigation. The manuscript of this paper as submitted by Mr. Rafter contains a considerable number of details, which have been to a certain extent generalized, and also gives a discussion of sewage purification in the United States, with descriptions of the works erected at various localities, together with an appendix containing a list of publications relating to sewage irrigation. The limit of 100 pages has, however, necessitated the dividing of the manuscript into two parts. The first constitutes this paper, while the latter has been held for publication in a future number of this series. It refers mainly to the results attained in various portions of the United States, and gives a few examples from the neighboring Province of Canada. The changes that have been made in Mr. Rafter's paper have been in the direction of adapting it to popular use, in order that the necessities and benefits of sewage irrigation may be more generally appreciated by the public.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

IRRIGATING CORN BY SEWAGE ON FILTER AREAS AT PLAINFIELD, NEW JERSEY

SEWAGE IRRIGATION.

By George W. Rafter.

IMPORTANCE OF SEWAGE IRRIGATION.

Owing to the rapid growth of urban population during the past few decades, and the consequent increase of pollution of streams from which water supplies are obtained, the subject of sewage disposal has come to be one of prime importance. As regards the United States, however, it is only within the past few years that the subject of sewage purification and its relation to the purity of streams has attracted general attention. In view of the large number of people concerned and the benefits to be derived from the dissemination of information on this subject, there is probably no topic relating to water supply and irrigation which is of greater importance to the country as a whole.

The citizens of all our municipalities are interested as a mere matter of sanitation in the innocuous disposal of sewage. Independent of commercial considerations, the towns should welcome any suggestion looking toward ridding them of what is in most cases a dead weight on the hands of the municipal authorities. The farmers, especially market gardeners in the vicinity of towns, should be able to utilize sewage with advantage to themselves, thus rendering beneficial what is otherwise a source of danger to health. It is the object of this paper[1] to point out to American farmers and to municipal authorities

[1]There is nothing especially new or original with the author in the methods of sewage irrigation which are here presented. It is merely proposed to describe, so far as possible in non-technical language and for the benefit of American farmers, not only what is being done to-day abroad, but also what is being done here at home. The author wishes in this connection to acknowledge his obligation to a number of sanitary engineers who have kindly placed at his disposal information and illustrative material embodied in this paper. In addition to courtesies received from gentlemen connected with the management and operation of sewage farms abroad, as acknowledged in the paper in connection with the discussion of the several farms described, the author is under special obligation to James Forest, esq., now honorary secretary of the Institution of Civil Engineers, for information as to how and where to see the best examples of sewage farming in England. Among American engineers to whom acknowledgment is due may be mentioned Samuel M. Gray, M. Am. Soc. C. E., of Providence; Allen Hazen, Assoc. M. Am. Soc. C. E., of Boston; Frank H. Snow, Assoc. M. Am. Soc. C. E., city engineer of Brockton, Massachusetts; George H. Carpenter, C. E., city engineer, Pawtucket, Rhode Island; Carroll Phillips Bassett, M. Am. Soc. C. E., civil and sanitary engineer, Summit, New Jersey; Benezette Williams, civil and sanitary engineer, Chicago; George H. Frost, C. E., business manager Engineering-News; M. N. Baker, Ph. B., associate editor of Engineering News; Col. George E. Waring, M. Inst. C. E., street commissioner, New York; and Harrison P. Eddy, C. E., superintendent of sewers, Worcester, Massachusetts.

the fact that under certain conditions sewage may be utilized with profit and to indicate in general terms how this may be done.

In the arid and semiarid portions of the West sewage utilization is of especial importance, for there every drop of water, especially during the summer season, is needed for the production of crops. The relatively small flow of the streams, combined with the warm climate, renders sewage especially obnoxious if not properly cared for, so that considerations of health and comfort are added to those of increased land values due to complete utilization of the water supply. The introduction of sewage irrigation in the West is more easily accomplished than in the East because of the general employment of water in agriculture. The first use of sewage in this connection in the West was probably at Cheyenne, Wyoming, in 1883. It has also been used at Colorado Springs and Trinidad, Colorado, at Fresno, Pasadena, Redding, Los Angeles, Santa Rosa, and Stockton, California, at Salt Lake City, Utah, and at Helena, Montana.

The popular idea, not only with us here at home but very largely abroad, is and has been that anything and everything connected with sewerage and sewage disposal is of so vile a character that it must be kept entirely out of sight. Out of sight, out of mind, has been the universal principle thus far. The immense aggregation of population in cities, however, by forcing the subject upon the attention of urban communities, has served to modify somewhat this popular misapprehension. At the present time the few persons who have thought out the rational view of these subjects hold that the old notion was, like many old notions, essentially wrong. Sewage is a great fact of existence, and the proper way is not to ignore it but to meet the problem on its merits, the same as other difficulties are met and overcome. In this spirit, in England, at any rate, it has become quite common to build the necessary works connected with sewerage and sewage disposal as ornamental as possible, and in the United States this plan has been likewise followed in a few places.

Sewage purification was first attempted in England about forty years ago. At that time extravagant and, in the main, essentially erroneous views were entertained as to the possibilities of its utilization in agriculture. Especially was this true as regards the manufacture of artificial fertilizers from the sludge of various chemical processes. Large investments of capital were made and concessions granted by towns to private companies, practically all of which were for processes of chemical purification. With very few exceptions these investments have all proved a dead loss. The purification of sewage by chemical treatment at a commercial profit has been found impracticable. In the meantime land processes, which have developed contemporaneously with the chemical purification processes, have in every sense held their own, until at the present time it can be

said that under proper conditions a fair profit may be made by the cultivator from the utilization of sewage in agriculture.

About twelve years ago the author began to collect information in regard to the pollution of streams and the purification of sewage, with special reference to the conditions existing in the United States. At that time, aside from the work done by the Massachusetts State Board of Health and that just begun by the city of Philadelphia, very little information was available as to stream pollution in this country; necessarily one studying the subject must go to the foreign sources of information, and for this purpose nothing better could be found than the voluminous English sanitary reports, issued from time to time by various royal commissions and by a number of the large municipalities of that country. But since about 1886 the subject of sewage purification and its relation to the purity of streams has received much consideration in the United States, so that at the present time we have over sixty purification works in operation. American data are therefore accumulating rapidly, and we may hope in a few years more to have arrived at a full understanding of the more important principles involved in sewage purification and the prevention of pollution of streams as applied to our special conditions.

The conditions here are quite different from those existing abroad. In the first place, the streams are much larger, and so far as the production of mere effluvium nuisances is concerned they can take larger quantities of sewage without offense, although it ought not to be overlooked that since many of our streams are the sources of public water supplies the effect of sewage pollution may be even more harmful than though effluvium nuisances were produced, which, however unpleasant to the sense of smell, are not always the source of special impairment of health. Again, it may be pointed out that land, even in the immediate vicinity of large towns, is much cheaper here than abroad. In a number of cases in England the lands utilized for sewage irrigation have cost as much as £400 to £500 per acre, whereas with us frequently suitable lands can be purchased within practicable distance of towns for from one-quarter to one-eighth of these figures.

The large amount of experience gained abroad should have weight and value. For this reason an attempt is herein made to present saliently the current European practice of sewage utilization. We have tried too often to work out for ourselves what is popularly known as the American method, ignoring the experience of others. We may thus attain unto knowledge in the course of time, but meanwhile many unprofitable investments will be made and money and time will be unnecessarily lost. In this respect the conditions are similar to those seen in the development of ordinary forms of irrigation in the West, where frequently expensive works have been built and operated without a knowledge of the water supply or other conditions. A very

cursory study of Old World irrigation would have saved considerable loss and resulted in more satisfactory results than those now attained. In many of these older countries, having physical and climatic conditions almost identical with our own, methods of agriculture and of controlling and utilizing water have been developed through the trials and failures of unnumbered generations. We are merely repeating many of their mistakes, and are only gradually coming to appreciate the fact that a more complete knowledge of the experience of the rest of mankind would be of incalculable value to us.

GENERAL PRINCIPLES.

The more important of the general principles discussed in this paper are brought together at this point for convenience of reference:

(1) Sewage purification is an imperative duty which municipalities owe to the owners of riparian rights, and which can not be neglected by municipalities without such an infringement upon those rights as it is now well established may be prevented by legal process.

(2) Sewage utilization should go hand in hand with purification. When operated with reference to all the necessary conditions, a proper degree of purification may be attained as well as satisfactory utilization.

(3) The proper method of utilizing sewage is, for purposes of irrigation, by means which do not differ, except in matters of detail, from those of ordinary irrigation as practiced abroad for centuries.

(4) In order to utilize sewage to the best advantage, the towns should construct, at their own expense, intermittent filtration areas on which the sewage may be efficiently purified when not required for use in agriculture. Farmers utilizing sewage in agriculture should be required to take it only as needed for the best results on crops.

(5) The theory of the action of intermittent filtration is in effect the theory of purification as effected by broad irrigation, the difference between the two being chiefly a matter of detail.

(6) In the purification of a strong acid sewage from manufacturing towns it may sometimes become desirable to treat the sewage by a chemical process before utilizing it in agriculture. For this purpose lime is the chemical commonly used.

(7) In case the effluent from sewage purification works or areas is to be passed into streams which are the source of drinking water for towns farther down, the degree of purification should necessarily be high. The experiments of the Massachusetts State Board of Health show that there is no trouble in removing from 95 to 99½ per cent of the organic impurity, as indicated either by the chemical constituents or by the bacteria. When as much as 99 per cent is removed, the sewage becomes chemically purer than the water of many wells, and there is, so far as known, absolutely no reason why it may not pass safely into a stream used as the source of a public water supply.

(8) Intermittent filtration areas are best constructed of coarse mortar sand, as shown by the experiments of the Massachusetts State Board of Health.

(9) Intermittent filtration is chiefly a biological process, in which the nitrifying organisms, with the assistance of oxygen and the minerals naturally in solution in sewage, resolve objectionable organic matter into mineral nitrates, etc., the whole process, when properly conducted, taking place without the production of objectionable odor. The conditions for successful treatment are, generally, intermittency of application and open spaces in the filtering material to which common air may easily gain access. Such filters may be expected to purify from 30,000 to 100,000 gallons per acre per day, the amount depending upon the quality of the material in respect to sand and water content, as defined by the studies of Mr. Allen Hazen.[1]

(10) Sewage may be purified by broad irrigation at all seasons of the year at any place where the mean air temperature of the coldest month is not lower than about 20° to 25° F., while by the use of intermittent filtration it may be purified fairly well down to a limit of 18° to 20° F., provided the sewage reaches the purification area at a temperature not lower than about 45° F.

(11) From the experience gained abroad it is clear that we may successfully cultivate almost any of the ordinary agricultural productions of the United States on sewage farms, due regard being had in every case to the special conditions required for each particular crop.

(12) The most efficient purification of sewage can be attained by its application to land.

(13) On properly managed sewage farms the utilization of sewage is not prejudicial to health.

(14) In comparing the results of sewage utilization as thus far obtained in the United States with the results obtained abroad it is clear that, generally speaking, we have not been specially successful. As one chief step toward a remedy for this we need to create in this country a class of sewage-farm managers who are thoroughly familiar with all phases of the question. Thus far the management of American sewage farms has been usually in the hands of committees of municipal councils having little or no knowledge of the real governing conditions.

(15) The experience in England, Germany, and France, and also that gained in this country, all points to intermittent filtration relief areas, on which any surplus sewage not required in agriculture may be purified, as the rational method of procedure.

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[1] From 30,000 to 100,000 gallons of ordinary raw town sewage may be so thoroughly purified that it may be admitted to streams from which public water supplies are taken. If a less thorough purification is required, or if the sewage has been previously treated with lime, from 200,000 to 300,000 gallons per acre per day may be successfully purified.

SEWAGE DEFINED.

Before proceeding to the main discussion, it is necessary to know the meaning of the terms in common use. By *sewerage* we refer to the general practice of removing the liquid and solid wastes of the human economy, as well as the washings of streets and manufacturing wastes, by water carriage. A *sewer* is the conduit in which, by the medium of water, such removal is effected. *Sewage* is the generic term, not only for the combined water and waste matter flowing in sewers, but also for the mixed solid and liquid matter handled either by pail or by pneumatic systems.

Ordinary city sewage contains a great variety of ingredients in addition to the waste water from kitchens, baths, laundries, and other domestic offices. In manufacturing districts it may contain the refuse substances of various manufacturing processes, the whole diluted with a considerable amount of water, to which, in rainy weather, in towns with combined sewerage systems, is added a large amount of sand and earth and organic matter from the street washings. With separate systems of sewers street washings are excluded, and the sewage, by reason of containing the house drainage only, has a much more uniform composition than is found in the sewage from combined systems; whence it results that the sewage from separate systems is somewhat more amenable to treatment, for two reasons: (1) because of more uniform composition; (2) on account of less variation in quantity. In case sewage is to be purified at sewage-disposal works, both these considerations lead to decrease in first cost of the works as well as to decrease in annual expense of operation. In case of utilization of sewage for irrigation, the same considerations lead to certainty and ease in the utilization as well as to decrease in the expense.[1]

In American cities, which use at least 60 to 100 gallons[2] of water per capita per day,[3] sewage is considerably more dilute than in foreign cities, where from 30 to 50 gallons per capita is more nearly the daily allowance. As remarked by Mr. Mills in the special report of the Massachusetts State Board of Health, we may say that the sewage of the average American town will contain something like 998 parts of water, 1 part of mineral matter, and 1 part of organic matter. The mineral matter, as it ordinarily exists in sewage, can not be considered as specially harmful, and from a sanitary point of view the object of

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[1] See Sewage Disposal in the United States, Rafter and Baker, Chapter VIII, "General data of sewage disposal," and Chapter IV, "The self-purification of running streams," etc., for detailed discussion of fundamental points only briefly touched upon here.

[2] In all cases by gallons is understood the United States gallon of 231 cubic inches, or 0.13368 cubic feet.

[3] For information as to the use of water in American cities and towns in detail, see the Manual of American Water Works. A few cases are cited on page 16, following.

sewage purification is chiefly to get rid of the one one-thousandth part of organic matter.[1]

Comparing several series of analyses, both American and English, it becomes apparent that ordinary town sewage in England is usually considerably more concentrated than that of the American towns. It is very important to bear this in mind in applying English data to American conditions. The elaborate experiments conducted by the Massachusetts State Board of Health at Lawrence, and which have been reported from year to year in the annual reports of that board from 1888 to the present time, indicate that there is a relation between the purifying capacity of different filtrating materials and the amount of impurity which can be removed from sewage of a given strength. This point is strongly brought out by the experiments conducted by the Massachusetts board. It follows, then, that if we prepare special areas of sewage purification in accordance with the indications of the Massachusetts experiments we may expect to apply somewhat larger volumes of average American dilute town sewage per unit of area than has usually been found expedient in English practice. If, therefore, we use English data without reference to the quality of the soil to which the sewage is to be applied, or of the sewage itself, we shall be likely to arrive, at times, at more or less erroneous conclusions.

As a summation of this part of the discussion, we may say that the chief object of sewage purification is to rid the sewage of the one one-thousandth part of organic matter which it contains, and that all of the appliances for sewage purification and utilization may be considered as directed toward this one point.

QUANTITY OF SEWAGE.

In considering processes for the utilization of sewage, either in agriculture or for its direct purification by chemical methods or by intermittent filtration, it becomes necessary to learn, first of all, what quantity of sewage may be expected from a given population, and, inasmuch as the flow of sewage will vary with the quantity of water supply, our first inquiry may be properly directed toward ascertaining the amount of water used in American towns. It may be pointed out, however, and, indeed, strongly insisted upon, that general discussion of this phase of the question can only be of use as indicating tested and approved methods of procedure. The conditions vary so greatly in different towns that each case must be taken by itself as a problem for special solution.

If we examine statistics of the average consumption of water per inhabitant in the various cities of the United States, as given in the Manual of American Water Works and in other publications, we

[1] See table in the Twenty-Sixth Annual Report of the State Board of Health of Massachusetts, 1894, page 457, for the average composition of the sewage used in the experiments conducted at Lawrence by that board from 1888 to 1894, inclusive.

learn that there are wide variations. Without attempting to show their extent here, we may cite the statistics of a few cities of the United States by way of illustration:

Average use of water in various cities of the United States.

City.	Population, 1890.	Daily use per inhabitant.
		Gallons.
New York	1,515,301	79
Chicago	1,099,850	140
Philadelphia	1,046,964	132
San Francisco	298,997	61
Buffalo	255,664	186
Washington	230,392	158
Allegheny, Pennsylvania	105,287	59
Lowell, Massachusetts	77,696	66
Fall River, Massachusetts	74,398	29
Cambridge, Massachusetts	70,028	64
Atlanta, Georgia	65,533	36
Dayton, Ohio	61,220	47
Troy, New York	60,956	125
Trenton, New Jersey	57,458	62
Portland, Oregon	46,385	203
Lawrence, Massachusetts	44,654	62
Manchester, New Hampshire	44,126	44
Williamsport, Pennsylvania	27,132	143
Birmingham, Alabama	26,178	162
Newton, Massachusetts	24,379	40

Many other cases could be cited from a vast mass of statistics bearing upon this subject now in existence, but the foregoing are sufficient to show that the use of water in towns, both large and small, does not follow any special law, and that the only way to proceed will be to consider each case on its merits. On this point we may say that usually the use is smaller in towns provided with meter systems than in those without, and, further, that in those towns where meters are being gradually introduced the tendency seems to be, on the whole, toward a reduction per capita of consumption; all of which again emphasizes the importance of studying each case on its merits.

In making arrangements for utilizing sewage in agriculture, or even for the purpose of purifying it in order to comply with sanitary requirements, it is very important to take into account the future growth of the town. The tendency of the last few decades has clearly been in the direction of great increase in urban population, as illustrated by the reports of the last census.

In addition to variations in quantity of sewage due to varying uses of water in public supplies, we may frequently expect to find variations due to infiltration of drainage water into the sewers themselves, which will of course increase the flow of sewage over and above that due to the water supply, and to leakage from the sewers through gravel and other porous material and through the seams of rocks, which tends to decrease the flow below the amount due to the water supply. Both of these sources of variation will frequently operate to modify conclusions based upon water supply purely.

According to Frederick P. Stearns, M. Am. Soc. C. E.,[1] the amount of ground water finding its way into the sewers of the main drainage system of the city of Boston is about 45 gallons per capita per day. This large filtration is due chiefly to the fact that many of the older sewers of Boston are built of either dry or relatively open rubble masonry, while some of them follow the threads of old water courses, both of these circumstances leading to relatively large contributions of ground water.

At East Orange, New Jersey, a separate system of sewers was carried out in 1886 and 1888. The infiltration as measured before any house connections were in use was, for 25 miles of vitrified tile sewers, about 2.5 gallons per second. For the main brick sewer, 4,000 feet in length, the infiltration was 5 gallons per second. The total infiltration from the whole system amounted at these rates to 650,000 gallons per day. The flush-tank flow was taken at 30,000 gallons per day, and after the house connections were made the house-sewage flow from the contributing population of about 15,000 was taken at 620,000 per day; hence the infiltration was 50 per cent of the total quantity.[2] The remedy for a leakage into the sewers of this character may be found in improved methods of laying the sewers themselves. In any case it may be pointed out that an addition to the sewage flow proper of 50 per cent in the way of ground water is an unnecessary addition to the expense of sewage purification, should any be required.

We will assume, as regards the present argument, that the sewers of a separate system may, with careful workmanship, be made practically impervious, and that the sewage flow will therefore be about represented by the amount of the public water supply. We will further assume that there is no good reason why, in a properly managed municipality, there should be used more than from 60 to 80 gallons of water per capita per day. At this rate the sewage flow of a population of 10,000 would amount to from 600,000 to 800,000 gallons per day. In combined systems where the sewers receive the rainfall as well as the sewage proper it will be necessary to provide, in any purification project, for taking care of and properly purifying a considerable portion of the storm water at each rainfall.

[1] Special Report upon the Sewerage of the Mystic and Charles River Valleys, as made to the State Board of Health of Massachusetts.

[2] See Inland sewage disposal, with special reference to the East Orange (New Jersey) works, by Carroll Phillips Bassett, M. Am. Soc. C. E.: Trans. Am. Soc. Civil Eng., Vol. XXV, p. 125.

STREAM POLLUTION.

It is a well-established principle of law that every riparian proprietor is entitled to have a stream of water flow by his realty as it is wont to flow by nature. From this principle we have derived the old and well-settled doctrine that to pollute a public stream is to maintain a common nuisance. The necessities and conditions of modern society have, however, tended to some modification of this principle as thus strictly announced, so that at the present time there are certain reasonable pollutions of streams, or, rather, there are certain specific cases in which a stream may be polluted to some extent without abrogating the essential force of the fundamental proposition. At the same time it must be remembered that the broad proposition that streams ought not to be polluted is on the whole sound.[1] Admitting such premise, we are forced to the conclusion that some form of sewage purification is necessary wherever an aggregation of human beings in thickly settled communities leads to the production of any considerable amount of sewage.

If, however, towns or manufacturing establishments are situated on tide water, there is no reason why the sewage may not be disposed of by discharging it into the ocean, provided such a discharge can be made without creating a nuisance along inhabited beaches, and also provided it is clear that such discharge is, on the whole, financially to the advantage of the community furnishing the sewage. But if on examining all the attendant circumstances it appears that the sewage can be profitably utilized in agriculture, then there is no reason why such utilization may not be made, even in the case of towns situated on tide water. We need, therefore, as a necessary part of our subject, to discuss the general question of purification of streams. This question has been the subject of a large amount of discussion in England, where interest in it may be considered as dating from the first report of the Health of Towns Commission, made in 1844.[2]

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[1] The legal aspects of stream pollution as the matter stands to-day are discussed in Sewage Disposal in the United States, Chapter VI. The attention of the reader is specially directed to the views of the Massachusetts Drainage Commission as there given. The report of that commission may also be referred to, though, as it has long been out of print, it is now difficult to obtain.

[2] This commission made two reports: The first, in 1844, published in two octavo volumes; the second, in 1845, also in two octavo volumes. These two reports may be taken as the beginning of sanitary science in England and in the civilized world generally. Previous to and at that time the condition of the English towns, especially in the manufacturing districts, as shown by the information contained in these two reports, was such that the present generation can only with difficulty realize it. These reports should be studied by any person wishing to compass the whole subject of sewage utilization, by way of showing the magnitude of the evil which has been combated and greatly mitigated since 1844.

Among the subjects which this commission was especially charged with investigating were the causes of disease among the inhabitants as well as the best means of promoting and securing the public health. The commission pointed out a large number of cases where stream pollution was undoubtedly the cause of insanitary conditions, and the notable sanitary reforms which have placed England as regards sanitary improvements easily in the front rank of nations have all been perfected since that date. During the same period the literature of sanitation has been enriched by a number of valuable reports in which every possible phase of stream pollution has been discussed.

Without referring here to all of the various commissions in detail, we may cite the Royal Sanitary Commission of 1869, and the Rivers Pollution Commission. The former recommended that any stream from which drinking water is taken should be effectually protected from sewage pollution. The principle laid down at that time has been gradually extended until we now formulate it by the statement that streams which are even likely to be a source of water supply ought not to receive sewage pollution, or, if they do, only under such regulations as will admit of immediate discontinuance of the pollution whenever the water is required for domestic purposes.

The Rivers Pollution Commission[1] in their report point out not only the evils of pollution by sewage proper, but also those produced by pollution from manufacturing refuse. As regards this second class of pollutions, from manufacturing refuse, the following classification can be made: Pollution by dye, print, and bleach works; chemical works; tanneries; paper making; woolen works; silk works.

The reports of the Royal Commission on Metropolitan Sewage Discharge and of the Royal Commission on Metropolitan Water Supply also contain much information relating to stream pollution.

In this country stream pollution has been generally discussed by the State boards of health of Massachusetts, Connecticut, Illinois, and some of the other States. In Massachusetts the State Board of Health made the following recommendations many years ago:[2]

(1) That no city or town shall be allowed to discharge sewage into any water course or pond without first purifying it according to the best process at present known, which is irrigation; provided, that this regulation does not apply to a discharge from sewers already built, unless water supplies be thereby polluted; and

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[1] Rivers Pollution Commission (first commission). This commission made three reports. The first report deals generally with the best methods of preventing the pollution of rivers, with special reference to the conditions prevailing at that time on the River Thames. The second report deals with the River Lea. The third report deals with the rivers Ayr and Calder. Five volumes in all, 4°, London, 1866–67.

Rivers Pollution Commission (second commission). Report of the commissioners appointed in 1868 to inquire into the best means of preventing the pollution of rivers. This commission made six reports in all. The first report (2 volumes) treats of the pollution of the basin of the rivers Mersey and Ribble and of the best means of preventing pollution therein. The second report is taken up with a description of the A B C process of treating sewage. The third report (2 volumes) discusses the pollution arising from the woolen manufacture and processes connected therewith. Whoever would understand this division of stream pollution in all its phases should study this report. The fourth report treats of the pollution of the rivers of Scotland, and gives special consideration, among other subjects, to the pollution arising from paper-mill wastes, etc. The fifth report (2 volumes) treats of the pollution arising from mining operations and metal manufactures. The sixth report treats of the general subject of domestic water supply of Great Britain. A large amount of information about water supplies from cultivated and uncultivated areas and the contamination of water from manured and unmanured, cropped and uncropped land, is given, the whole forming a vast body of sanitary information pertinent to present conditions. Ten volumes, 4°, London, 1870–71–72–74.

[2] Seventh Annual Report, 1876, p. 12. To illustrate the pollution to which a single stream is subject, reference should be made to the Eighth Annual Report of the Massachusetts State Board of Health. In this it is stated that on the Nashua River are 92 mills, employing 5,543 persons. This stream drains an area of 437 square miles, with an average population of 106.5 to the square mile.

The reports of the Philadelphia water department, from the eighty-third to the eighty-sixth, inclusive, may be referred to for information in regard to stream pollution.

provided also, that any intended discharge of sewage can be shown to be at such point that no nuisance will arise from it.

(2) That no sewage of any kind, whether purified or not, be allowed to enter any pond or stream used for domestic purposes.

(3) That each water design should be regarded by itself in the preparation of plans for sewerage and water supplies.

(4) That accurate topographical surveys always be made of all towns before introducing water supplies or sewers.

(5) That steps should be taken by special legislation, based upon investigations and recommendations of experts, to meet cases of serious annoyance arising from defective arrangements for the disposal of sewage.

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In the Tenth Annual Report of the Connecticut State Board of Health (1888), Prof. S. W. Williston, of Yale University, has given an excellent account of the wastes from manufacturing processes, which may be referred to as perhaps the most useful recent contribution to the literature of river pollution. At any rate, it easily ranks first among recent American contributions to that literature. Professor Williston takes up in his report the waste due to various manufacturing processes, such as brass working, iron working, paper making, woolen, cotton, and silk mills, and so on, and gives under each head the chief sources of pollution.

As to brass works, it is stated that they are productive of little sanitary injury to a stream, although the discharge of their chief waste, sulphate of copper, is the most poisonous to fish of any of the manufacturing wastes. Brass works, therefore, usually cause the fish to leave any stream which receives a considerable quantity of refuse from the works. Aside from sulphate of copper, the other waste products of brass works are acids and oils. In many of the brass manufacturing establishments, especially those using the electro-metallurgical process, considerable quantities of cyanide of potash and ammonia are used. Goods requiring electroplating are first treated with an alkali to remove any greasy matters adhering to the metal, and are then subjected to a dilute acid bath in order to remove the oxides from the surface. They are then placed in a cyanide of potash solution, which acts as the carrier in the deposition of the metal upon the surface plated.

Cyanide of potash is a virulent poison, and Professor Williston states that a sufficient quantity is annually employed in the Naugatuck Valley, in Connecticut, to destroy all the inhabitants of the United States. Most of it, however, is neutralized by the other chemicals used, so that it is doubtful whether its contaminating influence is very great.

In the manufacture of iron the only waste of importance is that from the pickling baths used for giving a nonoxidized surface to either wire or flat sheets which are to be galvanized. Such iron is dipped in a solution of dilute sulphuric acid and then washed in water, after which it is again dipped in a vat containing a heated solution of lime, to neutralize any small amount of acid not removed by the washing in water.

IRRIGATION ON SIDEHILL AS PRACTICED AT WAYNE, PENNSYLVANIA.

The chief waste from this process is sulphate of iron, which at many works is allowed to pass directly into streams, although not all of it is thus allowed to go to waste, as a number of the large rolling mills of the country have appliances for saving the sulphate of iron; as, for instance, the Cleveland Rolling Mill, at Cleveland, Ohio; the Ferric Chemical and Color Works, at Worcester, Massachusetts; and the Washburn & Moen Wire Works, also at Worcester. A large proportion of the crude sulphate of iron of commerce consumed in the United States is produced at these several works.

The waste products from paper manufacturing are both organic and inorganic in character. In mills using jute, gunny sacking and old rope, and other similar substances as the raw material, the organic wastes of the wash water may become a very serious source of pollution if discharged into small streams or if a considerable number of mills all discharge their wastes into a stream of considerable size. Caustic soda and lime are used for cleansing rags in places where rags are the raw material of paper manufacture. These wastes are usually allowed to pass into the stream. In mills using sulphite and wood pulps the wastes from the wash waters generally contain a considerable amount of objectionable substances, the bleaching process also requiring a considerable amount of chloride of lime, which, in this country at any rate, usually passes into the streams without treatment. The bleaching wastes are especially injurious to fish.

In a woolen manufactory the most serious wastes are those derived from the washing of the wool; constituting, as it does, chiefly organic material, it may be considered one of the most objectionable organic wastes. The raw wool of the ordinary grades, as it comes to the manufactory, contains a third or more by weight of organic matter; this is ordinary washed wool. Unwashed fine wools may contain as much as 50 to 60 per cent of organic matter, which is removed chiefly by scouring in alkaline solutions of soda, although in some mills urine is used in this process, as it is believed to give a softer finish to the manufactured article than can be obtained by the use of ordinary alkalies.

The woolen mills also furnish a large amount of dye waste, such as extracts of logwood, fustic, camwood, madder, etc., which are used in different methods of dyeing with various mordants, such as copperas, crude cream of tartar, bichromate of potash, alum, blue vitriol, and muriate of tin. After treatment in the dyeing vat, the wool is washed in running water and, usually, the contents of the vat are turned into the nearest stream. It is waste material of this sort that causes the chief complaints as to discoloration of streams by dye wastes. A certain amount of oil is also used in woolen manufacture, and more or less waste therefrom passes into the stream.

In manufacturing cotton goods the wastes are both organic and mineral, the former being the more serious. In the manufacture of

ginghams the following chemicals are commonly used: Sulphuric acid, nitric acid, muriatic acid, chloride of lime, sal soda, soda ash, bichromate of potash, alum, copperas, blue vitriol, lime, pearlash, stannate of soda, sugar of lead, indigo, cutch, sumac, alkali, soda, and the various aniline colors and dyes. Of the mineral matters, the most important are lime, chloride of lime, and bichromate of potash; of the organic dyestuffs, logwood. The waste from these various substances is usually allowed to pass without treatment into the streams.

In silk manufactures the raw silk as received is covered with a gummy substance which it is necessary to remove in order that the silk may possess the proper degree of pliableness. This silk gum, which is called sericine, constitutes from 20 to 25 per cent of raw silk and is mostly soluble in water. It is removed either by maceration or by scouring in a weak solution of soda. The refuse from these processes is usually turned into streams. The further processes of silk manufacture, as related to stream pollution, are those of dyeing, which are only of secondary importance. It is stated that there is less waste of dyestuff from silk mills than from mills manufacturing other kinds of fabrics.

In considering the effect of stream pollution we should bear in mind that all streams have some self-purifying power. Nature has provided in soils a natural agent for the innocuous resolution of organic matter into its simple constituent elements. The agent of nitrification exists in soils in vast quantities, and we may draw the conclusion that every rain washes these purifying agents into streams, where their work of destroying organic matter is continually going on, although not with the same degree of rapidity as in soils. One indispensable condition of the efficient action of the nitrifying agent is the presence of an adequate supply of oxygen. All natural waters contain more or less oxygen in solution, but unfortunately the stock is not large enough to admit of rapid action of the nitrifying agent. Hence it follows that, while it is true that the process of nitrification goes on in natural waters as in soils, it is also equally true that it proceeds much less rapidly there than in soils, with the result that a natural water is more easily overburdened with work of this character than a natural soil. This fact leads to the conclusion that soil is really the natural element in which to resolve objectionable organic matter into its simple, elementary forms, rather than water. Natural waters should be called upon to perform this duty only when no other means are available, it being remembered always that it is easy to overburden the purifying power of water in this direction.

It is still true that a stream may exert considerable self-purifying power, provided it is given time enough. This view is enforced by considering that in addition to the presence in our natural waters of the agent of nitrification there are also present certain classes of minute life which feed upon extraneous organic matter and which

without doubt resolve a considerable portion of it through the operations of the life process. The Entomostraca, Rotifera, and Infusoria are the principal agents assisting in such reduction. Of these the Entomostraca are probably the most important. This branch of our subject leads to biological studies of great interest and importance, but which for lack of space can not be more than referred to in this place.[1]

VALUE OF SEWAGE.

From an agricultural point of view the nitrogen, phosphoric acid, and potash are the most useful ingredients of sewage, and accordingly it becomes of interest to establish the quantity of these three elements which may be found in ordinary sewage. Taking that of about average composition,[2] a net ton may be expected to contain nitrogen to the amount of from 0.15 to 0.25 pounds; phosphoric acid, from 0.045 to 0.065 pounds; and potash, from 0.025 to 0.040 pounds. With nitrogen at 17 cents per pound, phosphoric acid at 7 cents, and potash at 5 cents, the theoretical value of the fertilizing ingredients of such a sewage would be, per net ton, from about 3.5 cents to 4.5 or 5 cents. Taking into account, however, the various losses of the nitrogen, which is not only the most valuable but also the least stable element, as well as the expense of distribution, we may conclude that the manurial constituents of sewage have an actual value, when applied to good advantage in agricultural utilization, of from 1 to 2 cents or perhaps 3 cents per ton. We should note that this is the manurial value only.

Independent of the manure, the water of sewage has also a distinct value for irrigation. But by reason of the variation in local conditions, it is impossible to make any general statement of value which will apply to all cases, although in a general way we may say, taking into account the manurial constituents as well as the irrigation value of the water, that sewage, when applied to land at the best advantage, may be considered, with the present understanding of things, as worth from 2 to 4 cents per net ton. In some cases, by reason of its value for irrigation, it may be worth several times these figures.

We learn, then, that the irrigation value of sewage may be quite as important as the distinctively manurial value, and it is believed that the recognition of this factor has placed sewage utilization on a somewhat different plane from that formerly occupied. In order to illustrate this point let us consider the matter briefly from an historical point of view.

When sewage disposal as a necessary concomitant of the sewerage

[1] For an extended presentation of this phase of the subject see discussion, by the author, of Dr. Charles G. Currier's paper on Self-purification of flowing water and the influence of polluted water in the causation of disease: Trans. Am. Soc. Civil Eng., Vol. XXIV, p. 70.

[2] See extended tabulations from Wolff and Lehmann in the first report of the Rivers Pollution Commission, p. 27. Also see Storer's Agriculture, Vol. II, p. 70.

of cities first grew up in England very extravagant views were entertained as to the commercial benefits to be derived from sewage utilization. Many hundred patents were taken out, mostly, however, on chemical processes, and large investments of capital were made, which have generally proved failures. Following these failures there was a reaction, during the prevalence of which it was held that sewage could not be utilized at a profit. When we examine the whole matter practically we find that the failure, in a commercial way, largely pertained to the chemical processes, although it should not be overlooked that many of the early sewage farms, by reason of poor management, unnecessarily expensive first cost, and other causes, have never been financially successful. We shall also see, farther on, that the best method of managing such farms has only recently been understood, which may be given as another reason why many of the early farms have not been financially successful. The net result of all this has been that many experienced engineers, sanitarians, and agriculturists have held that it was impossible to utilize sewage at a profit.

There is, however, another phase of the question. The main object of sewage purification is to keep streams pure and to preserve the health of the citizens of our cities and of the surrounding country. It has therefore been held, and very properly, that the real object of sewage treatment is purification and not utilization, and that utilization, by introducing commercial considerations, will inevitably tend to lower the degree of purification. It has been held, in short, that sewage purification is a right which one community or individual owes to another, independent of any question of commercial profit. And while this proposition is undoubtedly true, it is believed that, with proper understanding of all the elements of the problem, a satisfactory utilization may be also attained without lowering the standard of purification.

On this point the author's views have undergone some modification since he examined in detail a number of European sewage farms in the fall of 1894. Previous to that time he was disposed to believe that sewage disposal should be placed entirely on the broad plane of purification rather than on that of utilization. At the present time he believes, as the result of seeing what is being done on the best sewage farms of England, Germany, and France, that the agricultural value of sewage may be fairly utilized, and still a high degree of purification attained.

Since the first development of sewage utilization in England the trade in commercial fertilizers has also greatly extended, and many writers have taken the ground that at the prevailing prices of commercial fertilizers agricultural lands can be manured more cheaply by their use than by the use of raw sewage.[1] In regions where the distribution of the rainfall is such as to fairly meet the necessities of

[1] See Agriculture in some of its Relations with Chemistry, by F. H. Storer, Vol. II, on this point.

agriculture this is probably true, but it is believed, with the present experience, that in any region where the distribution of the rainfall is such that periods of drought are likely to occur at the critical period of growing crops, provided sewage can be delivered upon agricultural lands by gravity, or even by a moderate pumping lift, a commercial saving will be effected, due to the irrigation value of the sewage, over any gain that can possibly be obtained by the use of commercial fertilizers alone. If pumping is required, its cost may, of course, enter in as a modifying element. At any rate the author wishes to place this thought before the scientific farmers of the United States as one well worthy of their most careful consideration. He desires further to say that from the experience gained in other countries, as well as our own, he believes that frequently lands in the immediate vicinity of our cities and towns can be improved in productiveness more by the general application of sewage irrigation than by any other method at present open to our farmers.

It should be remembered, however, that the quality of soils will enter into the final solution of the problem. Those best suited for sewage irrigation are open, porous, gravelly soils, while heavy clay soils may demand so great an expense of preparation as to render sewage utilization, except in special cases, practically impossible. As already hinted, each location presents its own special problem, which, to some extent, will demand its own special solution independent of all other cases. It can not be too strongly insisted, therefore, that each case must be studied by itself on its own merits; hence the foregoing statements are to be taken as general statements rather than universally true propositions.

METHODS OF SEWAGE DISPOSAL.

As the result of a large amount of experience gained abroad, sewage disposal or purification has resolved itself into three general methods, which are known as (1) chemical precipitation, (2) intermittent filtration, and (3) broad irrigation. In the present paper we are not specially concerned with chemical treatment, except as at times an adjunct of irrigation; nor are we concerned with intermittent filtration, except so far as it may be considered an adjunct of irrigation. For completion of the subject, however, we may briefly describe the process of treatment known as chemical precipitation.[1]

CHEMICAL PRECIPITATION.

In this process the sewage is allowed to flow into large tanks, in which it is dosed with certain chemicals; these form with the organic constituents an insoluble precipitate, which in its descent to the bottom of the tank may, under favorable circumstances, carry down with

[1] More complete descriptions may be found in the several standard treatises recently issued, as, for instance, Crimp's Sewage Disposal, Wardle's Sewage Treatment and Disposal, and Rafter and Baker's Sewage Disposal in the United States.

it the suspended matter of the sewage as well as a portion of the dissolved. To apply this treatment on a large scale, extensive works with a large number of tanks, together with machines for grinding and mixing the chemicals, as well as special mechanical arrangements for mixing the chemicals and sewage and caring for the sludge, are required, the whole including what is commonly called the chemical treatment of sewage, although the complete process is in reality partly chemical and partly mechanical.

The reagents now generally used are common lime, sulphate of alumina, and ferrous sulphite. These reagents are used either singly or in combination, as may be required to fit the case of each particular sewage undergoing treatment. The action of the reagents in producing a precipitation of the organic matter is not fully understood, although in a general way we may say that when lime is used there

FIG. 1.—Mystic Valley Chemical Purification Works, showing sludge beds and effluent channel.

is a combination of some of the lime with free carbonic acid gas to form an insoluble carbonate of lime; also, probably, an additional part of the lime combines with a certain portion of the organic matters in solution to form an insoluble precipitate, which in its journey to the bottom carries down with it any portion of the suspended matters which have not entered into combination. The matter settling to the bottom is called sludge.

When sulphate of alumina is used, the precipitating effect is considered as due to a combination of the sulphuric acid of the sulphate of alumina with lime and other mineral bases existing naturally in the sewage. A flocculent alumina hydrate is also formed, which in conjunction with the mineral precipitate further entangles and carries down any suspended organic matter. At the present time, as a general statement, we may say that a combination treatment of lime and

sulphate of alumina is preferable for ordinary sewage to the use of either of them alone, although the composition of the sewage should be taken into account in deciding.

In the case of ferrous sulphate, in order to secure a precipitating action it is necessary either that the sewage be naturally alkaline or, if not naturally so, that an alkali be artificially added. The result of this treatment is the formation of a flocculent hydrated oxide which carries down with it the suspended organic matter as well as a portion of the dissolved.

In order to insure the best results in chemical treatment the sewage should be treated while fresh and the chemicals added to the flowing sewage, in order that they may become fairly incorporated before it passes into the settling tanks. There should also be enough tank space to insure a thorough precipitation. Inasmuch as the sludge must be frequently removed from the bottom of the tanks, the mechanical arrangements should be such as to permit of its removal without interruption of the works.

Methods of chemical treatment may be classified as (1) intermittent treatment in shallow tanks from 5 to 8 feet deep, in which, after the addition and incorporation of the chemicals, the sewage is allowed to remain undisturbed until the completion of the process, when the clarified liquid is drawn off the top, leaving the sludge at the bottom; (2) continuous treatment in a similar series of tanks through which, after the addition and incorporation of the reagents, the sewage is allowed to flow slowly, crude sewage with freshly added chemicals passing in at one end and purified effluent passing out at the other; and (3) vertical tanks through which, after the addition of the chemicals, the sewage rises slowly. At the present time the continuous treatment, in which crude sewage with freshly added chemicals passes into one end and purified effluent passes out at the other continuously, is considered, as the result of experience, to be the preferable method of applying the chemical treatment.

As to the tank capacity required, we may say that in systems which are arranged with reference to receiving a portion of the rainfall the daily capacity should be nearly 50 per cent of the average daily flow, an allowance of this kind giving some leeway for contingencies when required. With the sewage from separate systems of sewers less leeway will be required.

Various methods of disposing of sludge have been used. One is to pump it into basins, from which it is subsequently conveyed to adjacent areas for utilization as fertilizer. It is also frequently deposited in large open basins surrounded by embankments, from which, after the larger portion of the water has drained away, it is removed either for use as a fertilizer or to some other point for filling in low land, etc. The liquid sludge is also sometimes run directly onto agricultural areas, where it is easily disposed of by plowing in. It may also be mixed with combustibles and disposed of by burning. In some cases

it has been used to form compost heaps by mixing with earth, rubbish, vegetable mold, gypsum, stable manure, leaves, or other suitable materials. When disposal works are situated near tide water, the sludge may be disposed of by running it into dumping scows, which convey it to deep water for dumping. It may also be burned in a furnace similar to the garbage destructor, but for this purpose it requires partial desiccation before treatment. On the whole, the most practicable way of treatment is to compress it into solid cakes by the use of a filter press. In this form it is entirely innocuous, and may be stored, handled, or conveniently transported for use, either as a fertilizer or for filling in low lands or for other purposes. The liquid sludge, as it ordinarily comes from the settling tanks, contains from 90 to 95 per cent water and from 5 to 10 per cent solid matter.

The mixing of the chemicals with the sewage is effected either by the use of baffle boards in the conduit leading to the tanks, or, where this is impracticable, by the use of mixing wheels. As the problem is merely one of thorough mixing, it is unnecessary to discuss it at length. Usually very simple mechanical appliances are sufficient.

At the present time lime containing from 65 to 75 per cent available calcic oxide can be purchased in the eastern part of the United States at from $8 to $9 per net ton; ferrous sulphate or copperas containing 26 per cent of ferrous oxide can be bought at about $15 per net ton, and sulphate of alumina, containing 14 per cent of alumina, at about $25 per net ton. The exact price of these reagents of course varies in different localities as well as with the quality of the reagent itself.

In 1889 Mr. Allen Hazen, at that time chemist in charge at the Lawrence experiment station of the Massachusetts State Board of Health, carried out a very elaborate series of experiments on the chemical treatment of sewage. The details of these experiments may be found in the twenty-first annual report of that board, to which, inasmuch as we are not concerned other than generally with chemical treatment of sewage, the reader is referred for a more extended account. We may, however, refer to the following statement of costs per capita in comparison with degree of purification obtained, as given by Mr. Hazen.

Taking the percentage of albuminoid ammonia removed to represent organic matter, the experiments on chemical precipitation show that in addition to all suspended matter the following amounts of soluble organic matter may be removed:

	Per cent.
With lime, costing 30 cents per inhabitant annually	22
With copperas and lime, costing 30 cents annually	29
With aluminium sulphate, costing 30 cents annually	20
With aluminium sulphate, costing 40 cents annually	29
With lime, costing 27 cents annually	20
With copperas and lime, costing 20 cents annually	13
With copperas and lime, costing 31 cents annually	39
With aluminium sulphate, costing 23 cents annually	10
With aluminium sulphate costing 45 cents annually	47

By way of disposing in this place of the question of relative degree of purification attained by the different processes, it may be remarked that there is now a vast body of information—not only special experimentation like that at Lawrence, but results obtained in actual practice—all showing that land-treatment methods, when properly operated, easily remove all the suspended organic matter of sewage as well as from 95 to 99.5 per cent of the dissolved matter. As a problem of efficient purification, therefore, the superior efficacy of the land treatments may be conceded without further discussion.

INTERMITTENT FILTRATION.

In 1868 a commission, consisting of Sir William Thomas Denison, Edward Frankland, and John Chalmers Morton, was appointed to inquire how far the use of rivers or running waters in England for carrying off the sewage of towns and the refuse of manufacturing processes could be prevented without risk to the public health or injury to such processes in manufactures, and also how far such sewage and refuse could be utilized and got rid of otherwise than by discharge into rivers or running waters, or rendered harmless before reaching them. The commission was further charged with an inquiry into the effect on the drainage of lands and inhabited places of obstruction to the natural flow of rivers or streams as caused by mills, weirs, locks, and other hydraulic works, and into the best means of remedying any evils thence arising. The commission so appointed is commonly known as the Rivers Pollution Commission, although it was in reality the second of this name.[1] Dr. Edward Frankland, the chemist member of this commission, was at that time by far the ablest chemist in England, and the vast amount of original chemical investigation given in the commission's six reports is a monument to his genius for sanitary chemistry and to his capacity for work.

In the first report, issued in 1870, the commissioners discuss various experiments on filtration which had been carried out under the direction of Dr. Frankland. Among others, the statement is made that the practice of filtration of sewage through sand, gravel, clay, or certain kinds of soil, if properly carried out, is the most effective method for the purification of sewage to which reference had at that time been made. A series of experiments on soil of various character is also discussed in detail, from which it is concluded that the process of purification through soil is essentially one of oxidation, the organic matter being to a large extent converted into carbonic acid, water, and nitric acid.

As one of the necessary conditions of intermittent filtration, it is also shown that a continuous aeration of the filtering medium must be secured. In discussing this phase of the subject the commissioners point out that the inability to continually aerate the filtering

[1] See footnote on page 19.

medium is a chief reason why purification of sewage by upward filtration will necessarily be less effective than by the opposite or downward filtration; hence the name "intermittent downward filtration," as originally attached to this process. The theory is discussed in too much detail in the report in question to admit of more than casual mention here. As the result of the commission's work on this line, it was concluded that a new method of sewage purification had been brought out. On this point the commissioners remark in their summary that towns and manufacturers have the means of rendering the organic impurities dissolved in their waste waters so far harmless by slowly passing them through well-aerated filter beds as to admit of their being again useful for manufacturing purposes.

The experiments carried out in the commission's laboratory showed that a properly conducted system of intermittent filtration would cleanse town sewage sufficiently to enable it to be used for all but domestic purposes. The result of the treatment is a true oxidation, and consequently an entire transformation of nearly the whole of the organic matter in the sewage. From the remedial point of view the new treatment was therefore considered successful. But the commission remarks that, since sewage possesses high agricultural value, this method of treatment, if universally adopted, would be very wasteful, and is therefore only to be recommended on a small scale or where circumstances render any other process, such as sewage irrigation, difficult or expensive. The commission, however, believed that the operation of sewage purification by intermittent filtration could be conducted without serious nuisance.

While the commission thus announces a new and valuable discovery in sewage purification, still it expresses in the final summary the opinion that in all practicable cases broad irrigation should be used in preference to intermittent filtration, because, when irrigation is carefully and properly conducted, not only is sewage rendered inoffensive, but some return of profit may be derived from its employment. In the commissioners' opinion all the experiments made to that date went to show that sewage can be most beneficially employed as a manure, and that it is thus also most perfectly cleansed.

The Rivers Pollution Commission, while originating intermittent downward filtration and strongly recommending its use under proper conditions, still, rather singularly, did not propose a complete definition of it as a process of sewage purification. In 1882 a commission[1] was issued to George William Wilshere, the Baron Bramwell, Sir John Coode, and others to inquire and report upon the system under which sewage is discharged into the River Thames by the Metropolitan Board of Works, and whether any evil effects resulted therefrom; and if so,

[1] Metropolitan Sewage Discharge, Report of Royal Commissioners, 4 volumes of reports, minutes of evidence, appendices, etc., 4°, London, 1884-85. Presents every phase of the question of disposal of sewage of London as it existed twelve years ago.

what measures could be applied for remedying the same. This commission is known as the Royal Commission on Metropolitan Sewage Discharge. In its second report we find a definition of the difference between broad irrigation and intermittent filtration, in the following terms: Broad irrigation means the distribution of sewage over a large surface of ordinary agricultural ground, having in view the maximum growth of vegetation (consistent with due purification) for the kind of sewage supplied. Filtration means the concentration of sewage at short intervals on an area of specially chosen porous ground as small as will absorb and cleanse it, not excluding vegetation, but making the produce of secondary importance. The intermittency of application is a sine qua non, even in suitably constituted soils, wherever complete success is aimed at.

As to the value of intermittent filtration, the Royal Commission on

FIG. 2.—Filter area, with absorption ditches, as laid out in England.

Metropolitan Sewage Discharge states that, in its opinion, the process has great scientific merit and affords valuable practical advantages for the disposal of sewage in situations where broad irrigation is impracticable and where land suitable for filtration can be obtained. If, however, there should be a difficulty in obtaining sufficient area of land, the commission is of the opinion that, before applying it to land, sewage should be previously treated by some efficient process for removing the sludge. The recent studies of intermittent filtration by the Massachusetts State Board of Health have greatly advanced our knowledge of the true theory of intermittent filtration, although, as we have seen, the broad lines were well established by the Rivers Pollution Commission in its first report, issued in 1870.

Taking into account the present views, we may define intermittent

filtration as a natural process of biologically reducing the nitrogen of complex, nitrogenous, organic matter to the simple forms of mineral nitrates and, probably, free nitrogen, the reducing action being due to two minute bacilli known as the nitrous and nitric organisms or ferments. The immediate result of the work of the nitrous organism is to convert ammonia into nitrite, while the nitric organism converts nitrite or nitrous acid into nitric acid, which, uniting with mineral bases, immediately forms mineral nitrates. The organisms producing these changes exist naturally in soils, and when specially prepared areas are properly treated develop in the interstices in vast quantities.

NITRIFYING FERMENTS.

No more fascinating chapter of science can be found than that pertaining to the development of our present knowledge of the real office of the nitrifying ferments. For many years the subject has been one of prolonged study by a number of the leading chemists and biologists of the age. Among these may be mentioned Schwann, Schultze, Pasteur, Schloesing, Muntz, Heraeus, P. F. Frankland, Warington, Winogradsky, and the biologists of the Massachusetts State Board of Health, working under the direction of Professor Sedgwick in that board's laboratory at Boston. Beginning with the

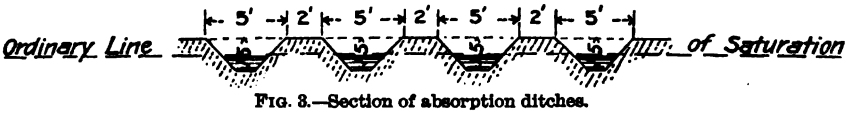


FIG. 3.—Section of absorption ditches.

work of Schwann and Schultze, as early as 1839, and ending with the work of Warington, Winogradsky, and the biologists of the Massachusetts board, we find a progressive advance from a knowledge, as the first step, that the decomposition of nitrogenous matter is due solely to the small vegetable organisms known as bacteria, to the final demonstration that the production of nitric acid is also due to a similar class of organisms. The complete account of the failures and successes encountered in the successive steps of the study is one of the romances of modern biology.

Without going into details, we will refer to two papers by Mr. Warington, one before the English Society of Arts, as published in that society's journal of April, 1882, the other as read before the British Association for the Advancement of Science at its annual meeting at Montreal in 1884. In his paper before the Society of Arts Mr. Warington set forth the theory of sewage purification by soil so clearly that we may draw upon it as perhaps, on the whole, the best concise general statement of the specific problem now under discussion thus far made. The paper begins by stating that dilute solutions of urine, which contain the essential constituents of plant food, undergo no nitrification when fully exposed to the air if only they have been previously

boiled and the air supplied to them is filtered through cotton wool. If we add a small particle of fresh soil to sterilized solutions of this character, no action at first appears, but after a while nitrification begins and the ammonia of the urine is converted into nitrate. This action proceeds best in the dark, and its full completion requires the presence of some mineral base, as, for instance, lime. A solution which has undergone nitrification is capable of producing nitrification in another sterilized solution which, without the addition of the nitrified solution, would remain unchanged. If we boil the soil or the nitrified solution, we destroy the power of causing nitrification. As a final point, Mr. Warington states that nitrification is confined to the same range of temperature which limits other kinds of fermentation. At or near the freezing point the production of nitrates proceeds very slowly, but increases in rapidity with a rise of temperature, reaching its maximum at 99° F. Above this temperature the rate of nitrification diminishes, nearly ceasing at 122° F., and entirely ceasing at 131° F.

Mr. Warington also states that the purifying action of soil on sewage is probably due to three distinct causes: (1) Simple filtration, or the separation of suspended matter; (2) the precipitation and reduction by the soil of ammonia and various organic substances previously in solution; (3) the oxidation of ammonia and organic matter by the agency of living organisms. It is considered that the last mode of action is the most important, as without it sewage matter would accumulate in the soil and the filter area soon loose its efficiency. The simple filtering power of the soil will depend upon its mechanical condition, while the precipitating power is a chemical function, in which the hydrated ferric oxide and alumina and the silicates of soils probably play the principal part. The oxidizing power will depend partly on its mechanical, partly on its chemical, and partly on its biological condition. We now know that a porous medium is not absolutely essential for nitrification and that sewage may be nitrified in a glass bottle or when passing over polished pebbles. Although porosity is by no means essential to the nitrifying power of soil, it is a condition having a very favorable influence on the rapidity of the process, porous soil of open texture presenting an immense surface, which will become covered with a thin film of the nitrifying organisms, and which, by reason of its porosity, will be well supplied with the air requisite for the discharge of other functions. This fact explains why nitrification takes place more rapidly in soil than in liquid.

In his paper before the British Association in 1884 Mr. Warington remarks that further proof of the ferment theory is afforded by the fact that antiseptics had been found fatal to nitrification. In the presence of a small quantity of chloroform, carbon bisulphide, salicylic acid, and, apparently, also phenol nitrification entirely ceases. The action of heat is also equally confirmatory. Mr. Warington also refers to experiments as carried out at the Rothamsted experimental

station, in which small quantities of the soil were taken at depths varying from 2 inches to 8 feet from freshly cut surface on the sides of pits sunk in clay soil. The soil so removed was at once transferred to a sterilized solution of dilute urine, which was afterwards examined from time to time to ascertain the degree of nitrification. From the results it appeared that in a clay soil the nitrifying organism is confined to about 18 inches of the top soil, and is most abundant in the first 6 inches. In a sandy soil, he remarks, we would expect to find the organism at a lower level than in clay, but at that time there was no direct evidence, although since then the later investigations have shown the presence of the nitrifying organisms at as great a depth in porous soils as 4 feet.

Another paper or series of papers by Mr. Warington which may be referred to is his six lectures on the investigations at the Rothamsted Agricultural Station before the Association of American Agricultural Colleges and Experiment Stations, at Washington, in August, 1891. In these lectures Mr. Warington brings the whole subject of nitrification down to date, but with such wealth of detail as to preclude more than a simple reference to the matter here. The reader interested in this particular phase of the subject can hardly do better than to study the lectures in question.

We have seen that Mr. Warington pointed out in his paper of 1882 that antiseptics are fatal to the life of the nitrifying organism. In the course of the experiments at Lawrence, Massachusetts, a number were made as to the effect upon nitrification of antiseptics, as well as other substances, among these being ammonium chloride, alkalies, acids, common salt, and sugar. The results indicated that many substances which would ordinarily be fatal to the nitrifying power of a filter if applied suddenly, can be efficiently treated provided the increase in quantity is gradual, thus giving the filter time in which to adapt itself to the various grades of work.

ESSENTIAL CONDITIONS.

We have seen that Mr. Warington pointed out in his paper of 1882 why porous soils would be much more favorable for intermittent filtration than those of close texture. We may now examine as to the quality of some best suited for such work.

In the Twentieth Annual Report of the Massachusetts State Board of Health we find stated as a fundamental proposition of intermittent filtration that sewage can be more efficiently filtered through open sand than through sand covered with soil, and that the upper layers of intermittent filtration areas should be of coarse sand, into which the sewage will disappear rapidly, leaving room for air to enter and come in contact with the thin laminæ of liquid covering the particles of sand. As regards the purification of sewage through the medium of nitrification, the chief points established are that the best results are

obtained in filters which have been for some time in work, thus becoming adapted to the special service they are to perform; that free oxygen is indispensable for success; that sewage is best purified when held in thin films upon or between sand grains and gravel stones; and that the period of greatest distribution of the ordinary sewage bacteria corresponds with the time of most active nitrification. The experiments also indicate that the nitrifying organism probably attaches itself in very thin films over the surface of the sand grains and gravel stones of the filter area, and that for complete nitrification the sewage should remain in contact with the nitrifying organism a short space of time. If while in such contact the conditions are favorable to the complete admission of oxygen, we may expect the purification to be very complete. So important is this consideration that Mr. Allen Hazen, in one of his reports, has formulated the indispensable conditions of sewage purification as depending upon oxygen and time. All other conditions, Mr. Hazen says, are secondary. Even temperature is only a minor influence. If the organisms for purification have attached themselves to the sand grains and imperfect purification then occurs for any considerable period, it is conclusive evidence, Mr. Hazen says, either that there is too small a quantity of oxygen present in the filter or that the sewage is passing through so rapidly as not to afford time for complete oxidation. In a practical way, therefore, such filters must be so operated as to insure a slow enough rate to give the necessary contact between the sewage and the nitrifying organisms, while at the same time insuring the presence of an abundance of free oxygen in the interstices of the filter. Moreover, we must not overlook the necessity for the presence of an alkaline basic salt, and the fact that the temperature of the filter area generally must be somewhat above freezing, although it is true that such filters will operate below freezing for considerable periods of time without entire cessation of the nitrifying process. As to the alkaline base, if it does not exist naturally in the filtering material used it may be added artificially. For this purpose common lime sown broadcast over the area answers every requirement.

The experiments at Lawrence have been carried out with reference to materials of varying degrees of coarseness. In some of the tanks coarse mortar sands have been used, while in others sands of medium quality, as well as fine sands, have been experimented upon. One of the most interesting special experiments is as to the filtering qualities of a very fine sand in situ.

For the purpose of this experiment a natural area of fine river silt of about one-third of an acre was prepared by partial underdraining with drains 60 feet apart, which were designed chiefly to catch samples of the effluent. This area is on the banks of the Merrimac River, near the experiment station at Lawrence, Massachusetts, with its surface several feet above the ordinary stage of the river. The few

underdrains laid were found of little use, because usually the liquid passes by them directly down to the plane of the water table. The surface of the location selected slopes at the rate of about 1 foot in 10 in one direction and about 1 in 100 in the other. A series of shallow trenches which follow the surface of the field are excavated in the original material. They are mostly made 1 foot wide top and bottom, with varying depths from 6 inches to 3 feet, and filled in with a coarse mortar sand. They are 5 feet apart, and are generally constructed with the surface of the coarse sand 4 inches below the adjacent original surface, except at the lower end, where, in a distance of 50 feet, the depth increases to 10 inches below the original surface. These trenches are each about 200 feet in length. The distance which sewage will flow in them varies with the amount applied and the amount of sediment upon the surface, which again varies with the quality of the sewage, the completeness of the nitrification, and the time elapsed since the surface was cleaned. As to the cleaning of the surface, it is found desirable that it be done occasionally, usually at periods of from one to three months. The removal of a quarter of an inch in depth from the surface of the coarse sand appears to be sufficient. During the winter the trenches have been covered with boards, with the result that the process of purification proceeded readily during the entire winter.

The result of this experiment indicates that in very fine sand of the quality here found from 50,000 to 60,000 gallons of sewage per day may be efficiently purified with a renewal of the sand in the trenches of perhaps 2 to 3 inches annually. Filters composed of either coarse mortar, sand or fine gravel, or coarse sand and gravel mixed may be expected, however, to filter from 80,000 to 100,000 gallons per day per acre.

Experiments with fine soil, with sand covered with soil, and with peat and loam and coarse gravel have all been carried out in great detail at Lawrence. The wealth of material relating to these different experiments precludes any adequate reference to all of them in this place. A few of the more interesting may be briefly referred to. For instance, one of the most important results brought out by the miscellaneous experiments is the fact that by systematically breaking the scum which forms on the surface of the filters a very much larger quantity of sewage can be purified without deterioration of the effluent than is possible when the scum is allowed to remain unbroken for long periods of time.

PERMANENCY OF SAND FILTERS.

As to the permanency of such filters, it is remarked that the leading fact of intermittent filtration is that the organic matters of sewage are destroyed instead of being stored in the filter, as is largely the case with other methods of purification. The experiments have further shown that the conditions allowing thorough purification of the

maximum volume with the best results are such that a small percentage of the more stable organic matters of the sewage resist the reducing action of the filter and tend to accumulate in its upper layers, until after a time the surface becomes choked to such an extent that the sewage will not sink freely below it, thus violating the fundamental principle of intermittent filtration. As a remedy it is suggested that temporary relief may be obtained by simply turning the surface under, although evidently an indefinite use of the same material would be impracticable if anything like a maximum quantity of sewage were treated. Since the organic material thus accumulating is confined entirely to the upper few inches of the filter, it is considered best to occasionally renew the upper layers of sand.

Experiments were also made as to the nature of the clogging material, with the result of showing that it may be divided into two classes, the fats and the sludges proper, the former being in effect the carbonaceous element and the latter the nitrogenous. The result of the experiments is to indicate that the fats themselves do not accumulate in the sand in such a way as to choke the filter. The possibility is pointed out, however, that instead of being completely oxidized and destroyed the fats may be oxidized to some stable compound which clogs the sand. The experiments apparently indicate some action of that sort which thus far has not been well defined. It has been found that clogging is in no way a serious matter, and that an efficient remedy is found, as already indicated, in either turning over or scraping the surface of the filter. The fact brought out that when the sand is unworked the fats slowly oxidize indicates either that the total filter area for any given case should be large enough to admit of a portion of the filter resting occasionally for a few months, or that the sand, if removed, can after a while be again used, although it is probable that ultimately it would require washing in order to remove slight accumulations of silt material carried in suspension by the sewage.

Perhaps as important experiments as any are those relating to the mechanical condition of the filtering materials. As assisting study in this direction, the modern systems of mechanical analysis have been of great value. Indeed, we may say that the recent work along this line has largely given an entirely new phase to all agricultural questions relating to the condition of the soil. In addition to the work on mechanical composition of the sands used in filtration as accomplished at the Massachusetts experiment station, chiefly by Mr. Allen Hazen, similar questions have been studied at the agricultural experiment stations of South Carolina and of Maryland by Prof. Milton Whitney.[1] The studies of these two gentlemen have added greatly to our

[1] See the Second Annual Report of the South Carolina Agricultural Station and the Fourth Report of the Maryland Station; also, as regards methods of making mechanical analyses of sands for filtration purposes, Twenty-second Annual Report of the Massachusetts State Board of Health.

knowledge of this subject, although the earlier work of Hilgard and Johnson is classic.

In order to estimate the filtering capacity of any given material, it is important to understand the air and water capacity of the filtering material when drained, the term "water capacity" being taken to designate the amount of water retained in the interstices after thorough draining. The efficiency of the filtering process depends largely upon these two elements. The amount of water will depend not only upon the closeness of the packing, but also upon its uniformity, and at any given time upon the amount of organic matter stored from the material filtered. The water capacity will also depend largely upon the size of the particles, the finer sands holding much water, especially at the bottom, while with coarse sand the amount held will be nearly constant from top to bottom.

Studies have been made as to the limitation of the size of single doses of sewage. With very coarse material the amount of sewage which can be applied at any one time is limited by the slight retentive capacity, the addition of too large a quantity leading to passage through the filter in too short a time. The conclusion from the studies is that the single dose should not exceed the water capacity of the material, because, if it does exceed such limit, a portion will pass through at once, first forcing out the water previously held, leaving the filter before complete purification can take place. If the air limit is exceeded, the oxygen in the filter is liable to be exhausted before the oxidation is complete.

As to the purification attained by intermittent filtration, the Massachusetts experiments show that very high degrees are reached easily. By way of illustrating the matter, we may simply state that sewage has been purified to the extent of removing from 95 to 99.5 per cent of the polluting material. Sewage containing from 500,000 to 1,000,000 bacteria per cubic centimeter has been so far purified of bacteria that the effluents have frequently contained as few as from 25 to 100 bacteria per cubic centimeter. In order to appreciate this degree of bacterial purification, we may consider that well waters in common use frequently contain from 2,000 to 3,000 bacteria per cubic centimeter. As regards chemical and biological considerations, there is therefore no reason why such sewage effluents are not fit to drink.

The body of information in regard to sewage purification by intermittent filtration which is presented in the several reports of the Massachusetts State Board of Health has become so extensive that one must be an expert to keep in mind the many interesting and valuable results brought out. As assisting the general reader, who may not care to travel through the several thousand pages of matter given in these reports, reference may be made to a very excellent summary of the results obtained from intermittent filtration during seven years' experimentation at page 497 of the report of 1894, where may be found

brief statements of yearly averages of the various kinds of filters experimented upon, as well as an outline of the most important features in the operation of each filter.

The subject of intermittent filtration has been discussed here because its theory of action applies to sewage irrigation as well, the chief difference between the two being in the method of application and in the agricultural results obtained. We shall see, however, that the two run together, crops being easily raised on filtration areas and the fields of sewage farms frequently irrigated when no crops are growing. The discussion of the theory of intermittent filtration is in reality, therefore, a general discussion of the theory of sewage irrigation. We shall see also that the agricultural utilization of sewage to the best advantage involves the use of intermittent filtration as an adjunct of broad irrigation.

IRRIGATION.

Ordinary irrigation, which consists in the application of water to the soil, in order to assist the growth of plants, has been practiced from the earliest days in Assyria, India, China, Egypt, Italy, France, Spain, and portions of England. Sewage irrigation, on the contrary, is, so far as known, a modern development. It has for its purpose the purification of the water which has been employed in carrying away the refuse of towns. The methods of applying sewage water do not differ greatly from those used in ordinary irrigation, except that by reason of the quality of the material which sewage water carries in suspension and solution special attention to the detail of the process is required, in order that the sewage water may not come in direct contact with the growing plants.

In selecting ground for a sewage farm account must be taken of the relative elevation of the farm and of the town, manufacturing establishment, or residence from which the material comes. Whenever possible, as a matter of economy, the farm should be selected with reference to the sewage reaching it by gravity. If, however, the location does not admit of such procedure, pumping may be resorted to, although this frequently will entail considerable additional expense in first cost of plant as well as in the annual outlay for operation and maintenance. In some cases, where land can be reached by gravity by going considerable distance or can be reached by pumping within a short distance, carefully prepared estimates, taking into account all the elements of first cost, as well as the annual cost of maintenance and operation, may show that it is cheaper to deliver the sewage a long distance by gravity than a shorter distance by pumping.

Formerly it was also considered important to select a sewage farm with reference to the surrounding inhabitation, because there was a prejudice against such farms on account of the assumed liability to effluvium nuisance. This objection has much less weight now than it formerly had, because experience has fully demonstrated that with

proper management a sewage farm is no more objectionable on account of bad smells than any other form of farming. The odor of manure is unpleasant, although not specially unhealthful. Undoubtedly there are many barnyards, both in town and country, which are more unpleasant to the sense of smell than well-regulated sewage farms. We may conclude, therefore, in the light of present experience, that an objection to sewage farms on account of serious effluvium nuisance is not well founded. We may further consider that all sanitarians agree that the proper place for disposing of such town refuse is on land. When applied there with due reference to our present information as to the nitrifying process, there is no reason for the production of specially bad smells.

For the best results the topsoil of a sewage farm should be of a

FIG. 4.—Distributing channel on the Berlin sewage farm.

permeable character, with a gravelly or sandy subsoil. If it be compact clay, the sewage can not enter, and the only purification attained will be that due to coming in contact with the soil by flowing over it. Clay soils, therefore, are not so satisfactory for sewage farming as open, gravelly soils, although, as we shall see in describing the sewage farm at Wimbledon, England, it is possible to so treat the sewage and prepare the farm as to attain a very high degree of purification even with clay soils, but the chance of doing this at a commercial profit is exceedingly small.

If not naturally level or of very uniform slope, a sewage farm for the best results should be leveled, so that the sewage may flow equally

over every portion. It should also be laid out with distributing channels, as shown in fig. 4, having a proper inclination in order to deliver the sewage readily to all parts of the farm. Formerly it was considered necessary that the carriers be lined with earthenware, concrete, or other impervious material, to prevent the sewage sinking into the ground during its passage along them, but now the more ordinary practice is simply to make earth ditches, with flat slopes. Fig. 5 illustrates a common form of pipe distribution. As to the best size of the field for irrigation, everything depends upon the quantity of sewage to be disposed of and the character of the soil. On this point the advice of a person of experience in sewage farming will be especially valuable.

As to the difference in soils for sewage purification, we may refer to some opinions expressed nearly thirty-five years ago. In 1862 a Parliamentary committee, known as the Select Committee on Sewage of Towns, took a large amount of evidence and reported at length in

FIG. 5.—Pipe-distribution system.

regard to the agricultural utilization of sewage. Among other eminent authorities called before this committee was Dr. Augustus Voelcker, at that time one of the leading agricultural chemists of England, who testified that sewage could be applied with great advantage on light, porous soils, and, indeed, on all soils which resemble in character such land; but on heavy clay land it could not be applied with advantage, especially when the cultivation was such as to produce in dry weather cracks in the clay, through which the liquid might penetrate to some depth in the soil.

Prof. J. T. Way, another eminent chemist, stated before the same committee that, though valuable materials were contained in sewage, they were coupled with a condition as to constant use in all weathers and at all times which obliged one to limit the use of them, and that if iron pipes were laid over a farm and the farmer given the privilege of using sewage when he liked to apply it, leaving it unused so far as the growing crops were concerned when not needed, there would be no doubt as to the value of sewage in agriculture.

Professor Way also said that under given conditions sewage is of immense value merely as water for irrigation purposes, while under

other conditions—for instance, in times of great rainfall—the water is so objectionable that one might better lose the manure than to be obliged to have the water. These opinions of thirty-four years ago are given here for the purpose of showing that even in the early days of sewage farming it was recognized that the necessity of caring for large amounts of water at all seasons might be a serious burden upon the success of such farming in a commercial way. The development of intermittent filtration since that time has, however, given us more thorough control of all the conditions than existed in 1862.

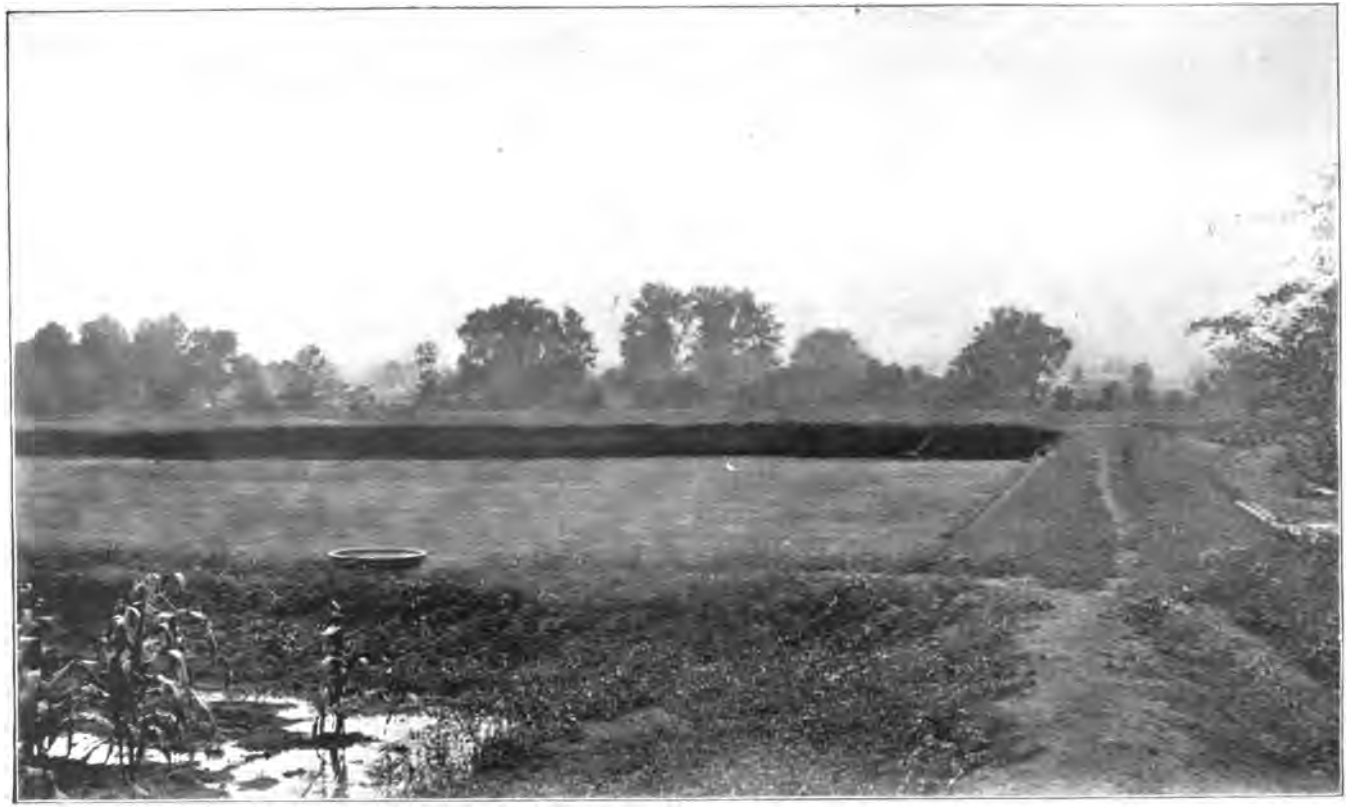
From our present understanding, the proper method of procedure is for towns to provide, where the conditions admit, intermittent filtration areas on which sewage can be cared for and efficiently purified whenever it is not needed for the purposes of agriculture. Such an arrangement will permit of using it under the conditions laid down by Professor Way; that is to say, the farmer may take it when he needs it and let it alone when it is not needed. As thus employed, there is no doubt that sewage irrigation may be made immensely profitable in all parts of the United States. We say all parts, because there is a popular notion that in the eastern part, at any rate, the rainfall is sufficient to meet all the requirements of agriculture. One needs, however, to study the history of irrigation in foreign lands only casually in order to learn that this impression, like many other popular impressions, is only in a moderate degree true. The author is decidedly of the opinion that irrigation occasionally applied, even in the East, would lead to a very great increase in the productiveness of farms.

By way of illustrating the foregoing proposition as to irrigation supplementing the natural rainfall, the conditions in the Po Valley, in the north of Italy, may be referred to. We have here an extensive plain on which irrigation has been practiced for over two thousand years. For 200 miles along the southern base of the Alps the rainfall in the early part of the year is usually sufficient for the spring crops. Later in the season the rainfall is less, but by the use of irrigation a second crop is raised after the first crop is removed in the early and middle part of the summer. In this way the total yield is nearly doubled.

FILTRATION AREAS NECESSARY.

In order to utilize sewage in the manner proposed, it will be desirable for municipalities to construct intermittent filtration areas at the expense of the municipality at large, on which sewage can be purified whenever not required for agriculture. During the season of actual growth, when sewage would be naturally used for irrigation, the filtration areas would be allowed to rest, thus perfectly fulfilling one necessary condition which we have already discussed in treating the subject of intermittent filtration.

Possibly the objection will be raised that under this arrangement the towns themselves would not realize a profit on the sewage. This,



FILTER AREAS AT PLAINFIELD, NEW JERSEY.

however, is not a matter of any moment. The towns, as we have seen, really owe it to the riparian proprietors on the streams below the points where sewage enters not to so foul the stream as to create a nuisance. It is a natural right of the riparian owners to demand that sewage pollution be prevented. It is a duty, therefore, on the part of towns to purify sewage before allowing it to enter streams. If in the process of such purification the towns can realize even a partial return, they have so much clear gain; they should look upon it as a partial recoupment of a necessary expense which otherwise would be much larger.

Experience has shown that there is no objection to raising crops on the intermittent filtration areas, and on several of the English sewage farms, as well as on those of Germany, this practice is quite common. It has also been done at South Framingham, Massachusetts; at Plainfield, New Jersey, and at other places in the United States. At South Framingham, in particular, the result of several years' experience is to indicate that Indian corn grows with the greatest luxuriance upon the filtration areas, so much so that in some years the standing crop has been sold in the field to the highest bidder at as much as from $30 to $40 per acre. At the same time the effluent from the South Framingham sewerage works, which flows into the Boston water supply, has been kept up to the proper standard of purity. The works at South Framingham are owned by the town.

OPINIONS OF FOREIGN COMMISSIONS.

Examples of this sort show the importance of approaching questions of sewage purification and utilization from a practical point of view, and with due reference to the recent information as to the effect of the nitrifying organism in preparing refuse substances for utilization by plant life. The problem takes on such new forms that much of the old information has little application. There are, however, a large number of opinions expressed in the past by government commissions and eminent sanitarians which are considerably enforced by the recent views. Let us refer a little in detail to several of these opinions which have been shown by the passage of time to be fundamentally sound. In 1857 a commission [1] was appointed to inquire into the best mode of distributing the sewage of English towns and applying it to beneficial and profitable use. This commission included among its

[1] Sewage of Towns Commission, Reports 1, 2, 3, 8°, London, 1858-61-65. These reports contain the details of careful investigations. Elaborate cultivation and feeding experiments were pursued extending over a period of several years, the results of which were presented in great detail in the second and third reports. In the appendix to the first report may be found an account of a visit made by a committee of the commission to Milan, Italy, for the purpose of examining the sewage utilization works at that place. This committee reported, under date of December, 1857, that the experience of the irrigation around Milan added a striking proof to that already obtained as to the value in agriculture of a command of pure water, and of the immense increase of that value obtained by the addition of sewage combined with the higher temperature derived by the liquid in its passage through the town.

members such eminent engineers and chemists as I. K. Brunell, Robert Rawlinson, Prof. J. T. Way, J. B. Lawes, John Simon, and Henry Austin. They studied the question in all its phases and carried out extensive experiments, which are detailed at length in their reports. In the final report, presented in 1865, the commission said that as a result of its labor and investigation it was of the opinion that the right way to dispose of town sewage is to apply it continuously to land, and that the pollution of rivers can be avoided only by such application; that the financial results of applying sewage to land differ under different local circumstances, because in some places irrigation can be effected by gravity, while in others pumping must be employed; also, because heavy soils, which may be alone available in some places, are less fit than light soils for sewage irrigation. The commission also expressed the opinion that where local circumstances are favorable, and undue expense is avoided, towns may derive profit from applying sewage in agriculture.

As a final summation, this commission states that wherever rivers are polluted by the discharge of town sewage into them, the towns may be reasonably required to desist from causing a public nuisance.

In 1865 another commission was appointed (referred to on p. 19), commonly known as the First Rivers Pollution Commission. It consisted of Robert Rawlinson, J. T. Harrison, and J. T. Way, who were charged with an inquiry as to how far the use of rivers and running waters in England for the purpose of carrying off the sewage of towns and populous places and the refuse arising from industrial processes and manufactures could be prevented without risk to the public health or serious injury to such processes and manufactures, and how far such sewage and refuse could be utilized other than by discharge into rivers or rendered harmless before reaching them.

In its report on the River Thames this commission suggests that the whole river be placed under the superintendence of one governing body, and that, after the lapse of a period to be allowed for the alteration of existing arrangements, it be made unlawful for any sewage, unless the same has been passed over land so as to become purified, or for any injurious substances or refuse from paper mills, tanneries, and other works, to be cast into the River Thames between certain limits defined in the report, and that any person offending in this respect be made liable to penalties to be recovered summarily. In their report on the River Lea the commissioners suggest that a similar arrangement be made for the more thorough control of that stream.

In 1868 the Queen's commission was issued to what is known as the Second Rivers Pollution Commission, whose work in the line of intermittent filtration has been referred to on pages 29 to 31. The scope of this commission's inquiry, as given on page 29, is seen to be the same as that of the First Rivers Pollution Commission. The Second Rivers Pollution Commission studied questions of sewage purification very

broadly, making six reports in all, which are the great mine of information as to river and stream pollution at this day. As regards these particular subjects, in no civilized country has work approximating to that of the Second Rivers Pollution Commission been performed.

In the summary to the fourth report, on the best means of preventing the pollution of rivers, the commissioners take the ground that the question of how to prevent polluting liquids from gaining access to running water could not be successfully answered without first defining just what is meant by polluted water; and that following this line, for the purpose of efficient legislation, an arbitrary line should be drawn between waters which are to be deemed polluting and inadmissible into streams and those which may be considered innocuous and therefore admissible to streams. The commission therefore gives certain standards of purity, which it is not necessary to reproduce, and states that such standards have been formed with the most careful regard for the interests of both towns and manufacturers. It expresses the opinion that the adoption of the methods proposed would not inflict any injury on manufactures, but might, on the other hand, save the manufacturers from inflicting injuries upon themselves. It is also pointed out that one of the most crying evils in manufacturing districts is the want of clean water, and that therefore every successful effort to make dirty water again usable is a clear gain to the manufacturing class as a whole.

In 1876 the English Society of Arts took up the study of various subjects connected with the health of towns, and, as an authoritative scientific society of the country, appointed a committee to report to the society in regard to the various questions involved in sewage utilization and the allied sanitary subjects. In its report the committee states as its opinion that where land at a reasonable price can be procured with favorable natural gradients, with soil of the proper quality and in sufficient quantity, a sewage farm, if properly conducted, is apparently the best method of disposing of water-carried sewage.

The committee also cautions the reader to bear in mind that a profit need not necessarily be looked for by the locality or municipality establishing the sewage farm, but that the farmer may be expected to reap profits from the operation. As to the sludge from precipitation processes, it is pointed out that from the manurial point of view it is of low and uncertain commercial value; that the cost of its conversion into a valuable manure will preclude the attainment of any adequate returns for the outlay and working expenses connected therewith, and that means must therefore be used for getting rid of it without reference to possible profit.

In 1882 the Queen's commission was again issued to what is known as the Royal Commission on Metropolitan Sewage Discharge. The scope of this commission's inquiry has been already referred to on

page 31, in our discussion of intermittent filtration. This commission reported that it was neither necessary nor justifiable to discharge the sewage of the metropolis in its crude state into any part of the River Thames, and that some method of precipitation should be used to separate the solid from the liquid portions of the sewage. As a preliminary and temporary measure, however, the liquid portion of the sewage remaining after the precipitation of the solids might be suffered to flow into the river at a period between high water and half ebb of each tide, and at no other time.

It is also strongly stated that the liquid so separated would not be sufficiently free from noxious matters to allow of its being discharged at the present outfalls as a permanent measure; it would require still further purification, which, according to present knowledge, could be accomplished efficiently only by applying it to land. Because of the difficulty of obtaining sufficient area for irrigation in the vicinity of London, the commission was of the opinion that this additional purification could be best effected by intermittent filtration, for which, from the information at hand, it was concluded that sufficient area was available, at any rate within convenient distance of the northern outfall. As to the southern outfall, the commission was unable to state from its investigations the quantity of available land; in case of insufficient land available, the clarified effluent of the southern outfall was to be conveyed to the north side by a conduit under the river.

In 1892 the Queen's commission was again issued to what is known as the Royal Commission on Metropolitan Water Supply,[1] which was charged with inquiring into the present source of supply of the metropolis and as to whether the quality and quantity were adequate, etc. This commission included among its members such eminent sanitarians as Sir George Bartley Bruce, George H. Hill, and James Mansergh. In summing up the matter this commission said that all possible vigilance should be exercised to prevent unnecessary contamination of the rivers Thames and Lea and their respective tributaries, as well as to insure the thorough treatment of all sewage, before it is allowed to pass into the rivers, by the most efficacious methods that experience and science may dictate.

The Royal Commission on Metropolitan Water Supply also remarked that advances had been made during the past twenty-five years in the construction of sewage works in the valleys of the Thames and Lea; that where such works had been constructed on an efficient system the sewage could be so dealt with at all times, except those of flood, that the effluents were clear and innocuous. It should be borne in mind that this opinion is expressed by a commission which included

[1] Metropolitan Water Supply, Report of Royal Commission on, 6 volumes, general report, minutes of evidence, appendices, index, plans, etc., 4°, London, 1893. The most recent and extensive information as to pollution of streams and its effect on the water supply of the metropolis as applied to the rivers Thames and Lea, from which that supply is drawn.

in its membership some of the most eminent sanitarians of the present day, and that the streams into which the sewage effluents pass are the sources of the water supply of the largest city in the world.

In 1874 Sir John Hawkshaw was commissioned to inquire as to the pollution of the River Clyde and its tributaries and how far the sewage refuse from the towns and manufactories could be utilized and got rid of without running into streams, etc. In his report it is pointed out very forcibly that those who own and manage manufacturing establishments have them wholly under control, and that they can therefore provide and enforce the necessary provisions and regulations for removing the nuisances which they so often create, and that by reason of this fact there can be no necessity for the fecal matter from such establishments being passed into the streams. He also points out, as has been done by a number of other commissioners, that wherever large populations are gathered and numerous manufactories exist on the banks of any river, combined action should be taken to secure the waters of the stream from pollution as far as practicable. As a mere matter of fairness the manufactories and all works and establishments similarly situated should be treated alike.

In 1875 the president of the English Local Government Board requested Robert Rawlinson and Clare Sewell Read to report to the board as to the several modes of treating town sewage. The report, submitted in 1876, is one of the most valuable contributions to the literature of sewage disposal thus far made. Among the conclusions Messrs. Rawlinson and Read point out: (1) That the scavenging, sewering, and cleansing of towns are necessary for comfort and health, and involve in all cases questions of how to remove town refuse in the safest manner and at the lowest expense. (2) That the retention for any lengthy period of refuse and excreta in private cesspits or in cesspools, or at stables, cowsheds, slaughterhouses, or other places in the midst of towns, must be utterly condemned. * * * (3) That the sewering of towns and the draining of houses must be considered a prime necessity under all conditions and circumstances. * * * (4) That most rivers and streams are polluted by the discharge into them of crude sewage, which practice is highly objectionable. (5) That as far as they have been able to ascertain, none of the existing modes of treating town sewage by chemicals appear to effect much change beyond the separation of the solids. * * * (6) That so far as examined none of the manufactured manures made by manipulating town refuse, with or without chemicals, pay the costs of treatment. * * * (7) That town sewage can best and most cheaply be disposed of and purified by the process of land irrigation for agricultural purposes where local conditions are favorable to its application. * * * (8) That land irrigation is not practicable in all cases. * * * (9) That towns situated on the seacoast or on tidal estuaries may be allowed to turn sewage into the sea or estuary below

the line of low water, provided no nuisance is caused and that such mode of getting rid of sewage can be justified on the score of economy.

The foregoing include the opinions of practically all the leading sanitarians of England for the last thirty-five years, and, as will be seen, such opinion has been unanimous that the preferable mode of purifying town sewage is by application to land. So overwhelming is this evidence that we must, in the future, consider this part of the subject as what the lawyers call res adjudicata—a proposition absolutely settled and no longer to be called into question. The progress of the recent views to which we have already referred has assisted in taking this proposition out of the realm of controversy.

In passing we may remark that similar opinions have been expressed by German, Italian, and French Government commissions; but these latter all fall so entirely within the line of the view taken by the several English commissions that it is unnecessary to cite them here,

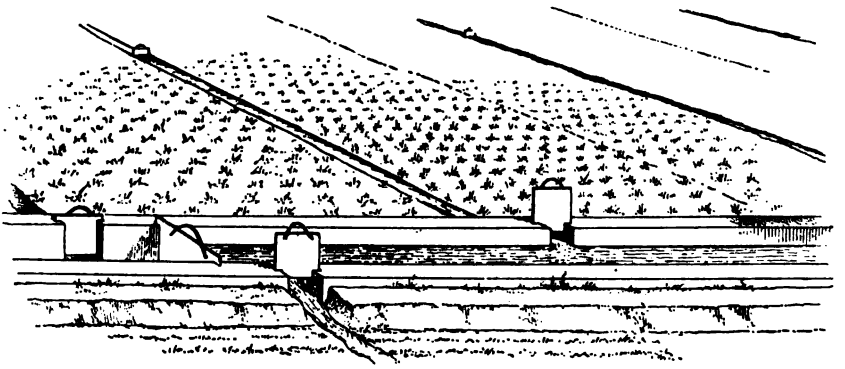


FIG. 6.—Ridge-and-furrow beds, with cropping.

the more especially because, sewage disposal having originated in England, the commissions of other countries have in their reports essentially followed the English views.

METHODS OF APPLYING SEWAGE.

As already stated, the methods of applying sewage in broad irrigation are substantially those of ordinary irrigation, with the exception of the necessity for closer attention to the detail. The principal special systems of irrigation used in sewage farming are known as (1) the ridge-and-furrow or bedwork system and (2) the catchwork system. Great variations from these two systems may, however, allowed.[1]

Figs. 6 to 13 illustrate a number of different methods of applying the sewage. We may also refer to the pipe-and-hydrant system, as

[1]For methods of laying out land applicable to sewage farms, see Les Irrigations, by A. Ronna (3 volumes, 8°). This is the most recent of the French text-books, and treats the preparation of land in full detail.

well as to the level-bed system, used when the filtration areas for intermittent filtration are utilized for raising crops.

In laying out land for the ridge-and-furrow system a series of slope beds are prepared, along the top of which supply carriers are laid, which are formed with level edges, so that the water flows over in a thin film and so on down over the slope beds with uniform depth. Such ridges are made in couples, with the slopes varying from 1 in 50 to 1 in 150. The amount of slope to be given in any particular case

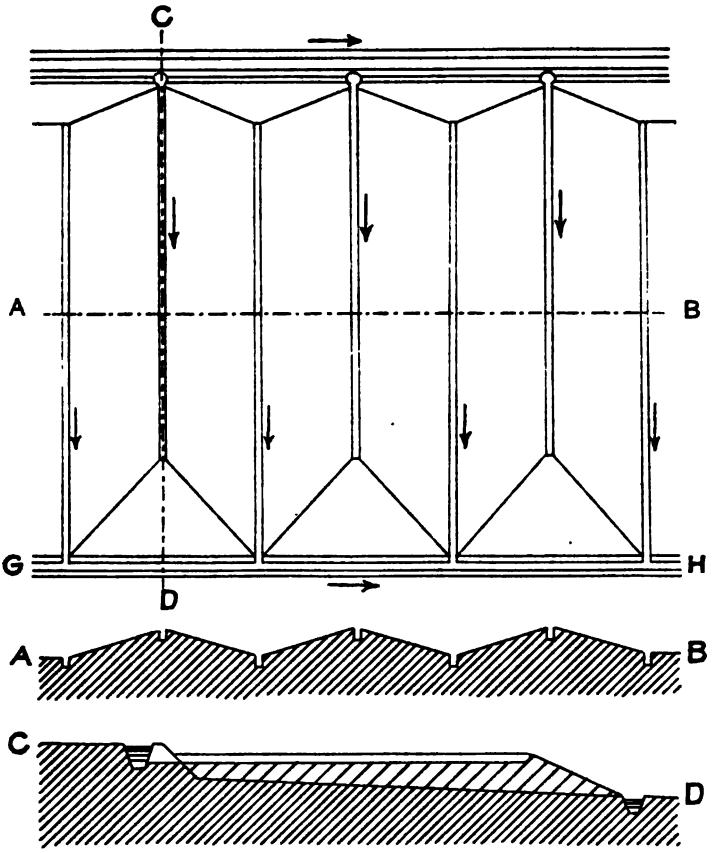


FIG. 7.—Plan and sections of ridge-and-furrow irrigation (Ronna, p. 438).

is purely a matter of judgment, in which the controlling factor is the porousness of the ground to be irrigated, the object of the slope being to insure that the water reaches in sufficient quantity all parts of the bed to be irrigated. Common dimensions of the beds are a total breadth of from 30 to 40 feet, or a breadth of slope on each side of the ridge of from 15 to 20 feet, although in exceptional cases, depending on just the use to which the beds are to be placed, the beds may be made larger. The length may be any convenient dimension suited

to the contour of the area prepared. Land under such beds may be underdrained in accordance with the rules for underdraining which apply in ordinary farming, though in deciding whether or not to fully underdrain any given area it should be remembered that drainage increases the porousness of the soil.[1]

At the foot of the slopes a furrow is formed, which receives any sewage not absorbed in the passage over the beds and conducts it away to another and lower series of beds or to the outfall, as the case may be. Ordinarily the surface water of one irrigation should be passed over several beds in order to insure thorough purification. This is especially important where the beds are made of the sizes indicated in the foregoing. The thorough removal of the water at the

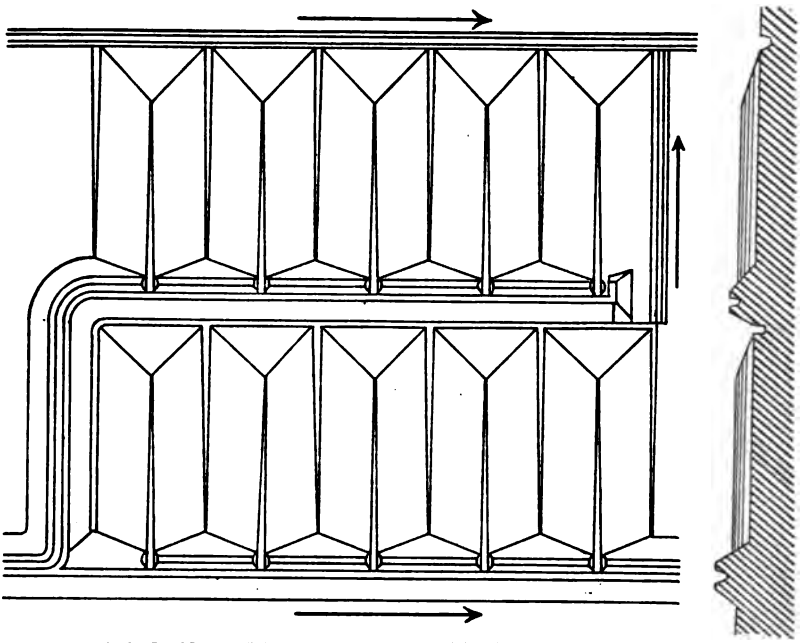


FIG. 8.—Double-bed ridge-and-furrow irrigation, with direct or secondary irrigation on the lower bed (Ronna, p. 449).

foot of the slopes, as well as the prevention of water-logging of the land, is insured by making a furrow at the foot of the slopes of ample dimension and with fall enough to produce quick drainage. Figs. 7 and 8 show the arrangement of the ridge-and-furrow system of irrigation.

In the catchwork system, which is more especially adapted to steep and irregular land, the liquid is delivered at the highest point of the area, the same as with ridge-and-furrow, a main carrier with level lip

[1] French, Henry F.: Farm Drainage; The Principles, Practice, and Methods of Draining Land, etc., 12°, New York, 1884. Waring, Col. George E., jr.: Draining for Profit and Draining for Health, 2d ed., 12°, New York, 1883.

on the lower side, along the highest contour, permitting the irrigation water to overflow the edge when dams are placed temporarily at various points on its course. At some distance lower down a catch gutter is formed on the contour, into which the unabsorbed overflow of the main carrier is caught as it flows downward. A damming of the catch gutter at suitable intervals causes it to overflow to the second, the same as in the case of the main carrier, and so on down to

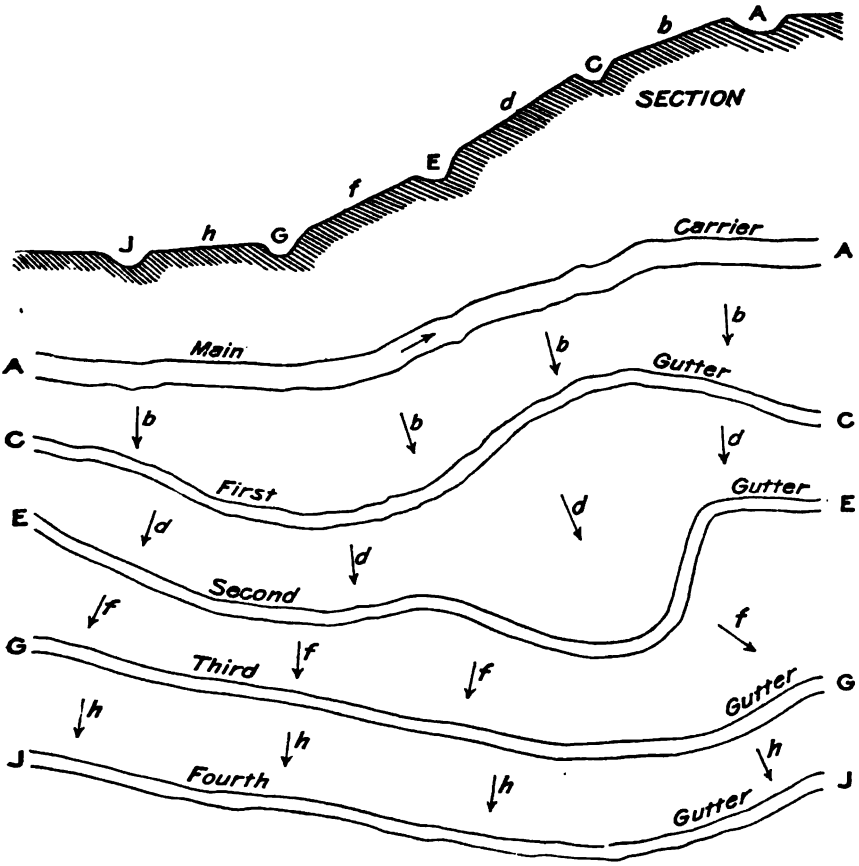


FIG. 9.—Catchwork system of irrigation.

the lowest contour of the area irrigated. The detail of this operation is illustrated by fig. 9.

According to Mr. Burn,[1] the great difference between the ridge-and-furrow system and the catchwork system is in the laying out of the ground. In the catchwork system, although the natural inclination of the ground is taken advantage of in the most direct and simple manner, still a considerable inclination is necessary for its successful application. The ridge-and-furrow system, on the other hand, is

[1] Burn, R. Scott: Outlines of Modern Farming, 6th ed., 12°, London, 1888. Treats extensively, among other subjects, of the utilization of town sewage, irrigation, etc.

more especially applicable to flat ground, such as is usually found in valleys or along the banks of rivers. In this system the necessary inclination is given by artificially throwing up the ridges, and the skill with which one part is taken advantage of to make up the deficiencies of another part will determine the degree of economical success. Generally speaking, the catchwork system is much cheaper than the ridge-and-furrow system, and at the present time the ridge-and-furrow system is only used where the ground is exceedingly flat or where for some special purpose the catchwork system is deemed to be specially undesirable.

Mr. Burn calls attention to certain points to be observed in laying out beds for the ridge-and-furrow system, as follows: If land

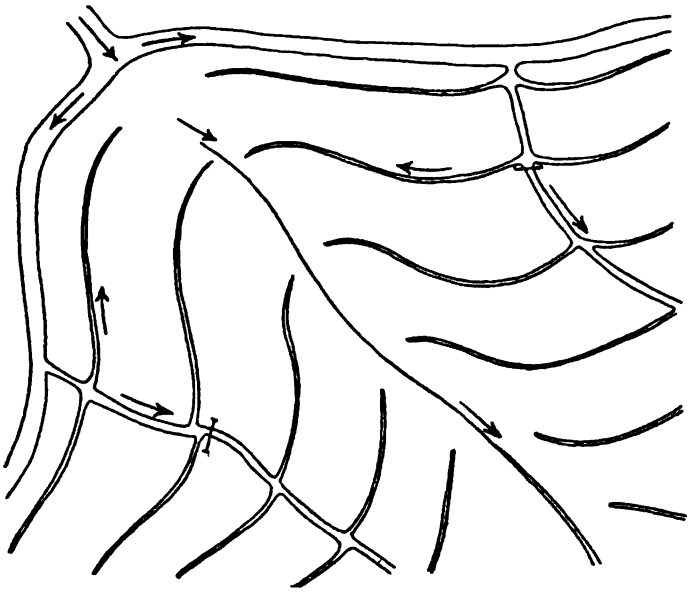


FIG. 10.—Distribution system adapted to irregular land (Ronna, p. 392).

intended for permanent meadow has a covering of sod, this should be removed by cutting into strips some 15 or 18 inches wide and placing carefully at one side. The inclined beds should next be made and the levels properly adjusted; then the channels of supply and the drains for leading off the water when used should be marked off. Cutting out of these may then be proceeded with, taking care in beginning the leading channels of supply that the soil taken out from these and the drains be carefully spread over the inclined surface. After the channels are all cut, if the ground is to remain down in meadow, the turf may be replaced. This work should be done with care in order to prevent irregularities of the surface. In all this work the point to be observed is that all parts of specially prepared surface shall receive their due supply of sewage. If hollows are left, the

sewage will be likely to collect therein and become stagnant. Mr. Burn expresses the opinion that the objections which have been frequently raised to the rankness of sewage-grown grass have had their origin chiefly in the badness of the plan adopted for applying the sewage. If this is true, it is obvious that the small additional expenditure necessary to prepare the ground properly will be repaid.

As to the relative costs of preparing land for ridge-and-furrow irrigation, it has cost in England, in some cases, as much as from $100

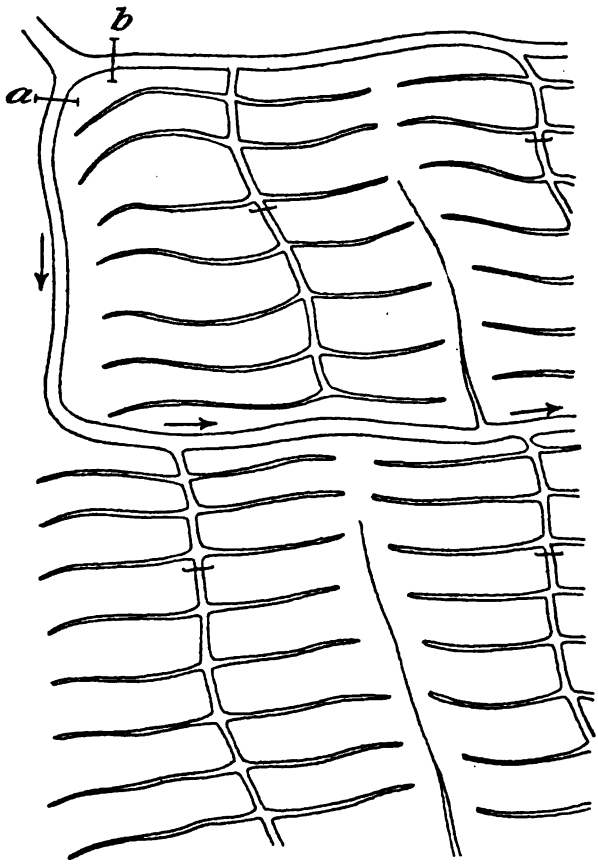


FIG. 11.—Double system of contour distribution controlled by end gates (Ronna, p. 395).

to $250 per acre, while catchwork systems have been carried out for from $10 to $25 or $30 per acre. The difference in price alone would lead to the use of the catchwork system and modifications of it in this country.

In a pipe-and-hydrant system of distribution a series of pipes is laid according to such a system (depending upon the topography) as will admit of reaching every point of the area to be irrigated with sewage. Formerly iron pipes were used for this purpose, but at the present

time terra-cotta or vitrified tile pipes are quite commonly used. In order to render the irrigation of the field as convenient as possible, hydrants are placed at proper points, fitted with the usual coupling for connecting hose. Sewage is forced through these pipes, either by steam power or gravitation, as the case may be, and distributed to the surface of the fields by means of hose.

In a gravitation system a receiving tank is usually placed at a convenient elevation above the area to be irrigated, from which mains are laid to different parts of the irrigated area. In such a system the power with which the sewage flows from the hydrants is necessarily fixed by the height of the tank, but in a pumping system the power can of course be varied the same as in any other application of pump-

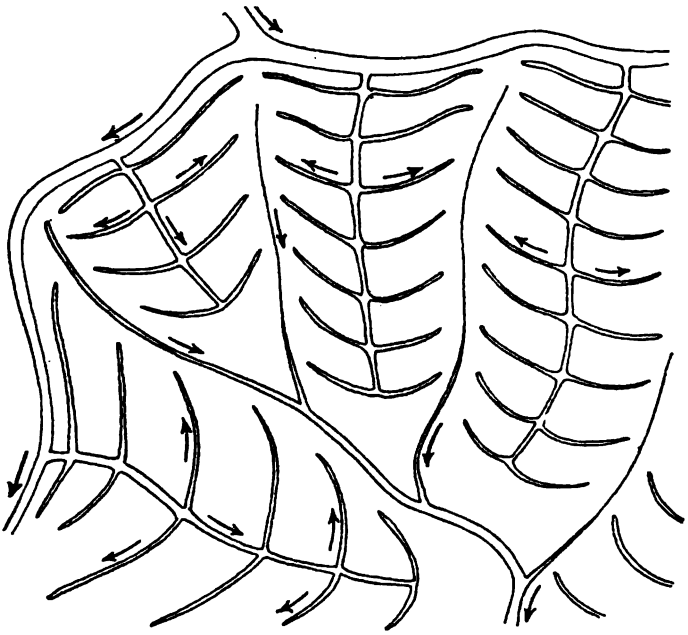


FIG. 12.—Distribution adapted to irregular ground (Ronna, p. 399).

ing. The detail of arranging such systems can not be given except in a very general way, because of differences in local conditions, but it will readily present itself to any engineer skilled in this class of work when the necessary preliminary data are placed before him. In England a large number of pipe-distribution systems have been carried out, while in this country the distribution at the Pullman, Illinois, sewage farm is effected in the same manner. The scarcity of water in southern California has also led to a considerable use of pipe systems there for the distribution of ordinary irrigation water, especially in the vicinity of Los Angeles.

One of the most complete systems of this kind is on a sewage farm at Rugby, England. This was established by Mr. G. H. Walker, who

entered into an arrangement with the borough of Rugby to take the town sewage, which at the time of laying out the farm amounted to about 160,000 gallons a day. All cesspools were abolished in the town, and even the humblest cottage was provided with water-closets, so that the entire refuse of a population of 7,000 was delivered into the sewers.

The sewage flows from the town into an open brick reservoir 50 feet in diameter and 12 feet in depth, from which it is forced by steam pressure into a system of cast-iron pipes led over the farm. The

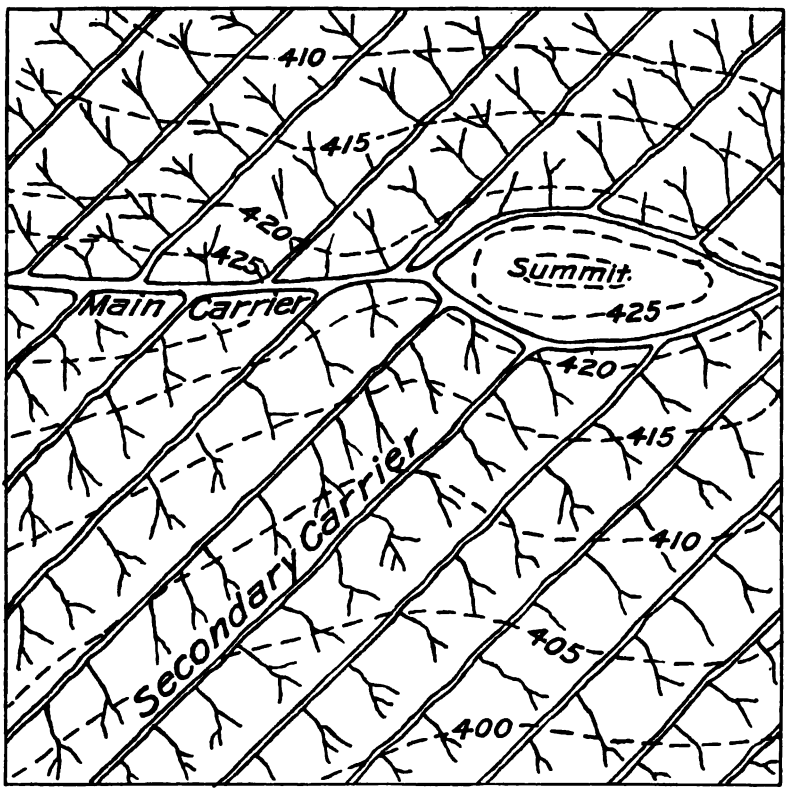


FIG. 13.—Distribution adapted to a field with ridge.

greatest elevation to which the sewage is pumped is about 60 feet above the reservoir, although a considerable portion of the land is over 20 feet above that level, and some of it as much as 20 feet below. The engine works a small air pump for the purpose of agitating the sewage in the receiving reservoir and preventing the deposit of solid matters.

The distributing pipes are laid over 420 acres of land, chiefly in grass, and comprise about 5½ miles, or about 691 feet per acre. The main distributary is 6 inches in diameter, with branches 3 inches in diameter. The total number of hydrants is 66, fitted with couplings

for attaching hose from time to time to distribute the sewage in the neighborhood of each. The works originally cost about $32 per acre, but with the experience gained from these and other works it is believed that similar works could now be carried out for $25 or less per acre. Probably, by the use of terra-cotta pipe for that portion of the distribution system not required to take high pressure, the cost

FIG. 14.—Section of intermittent filtration area.

of such a system, with favorable topographical conditions and a large area, could be brought within $15 to $18 per acre. The cost of distribution is stated at not exceeding 1 cent per ton of sewage.

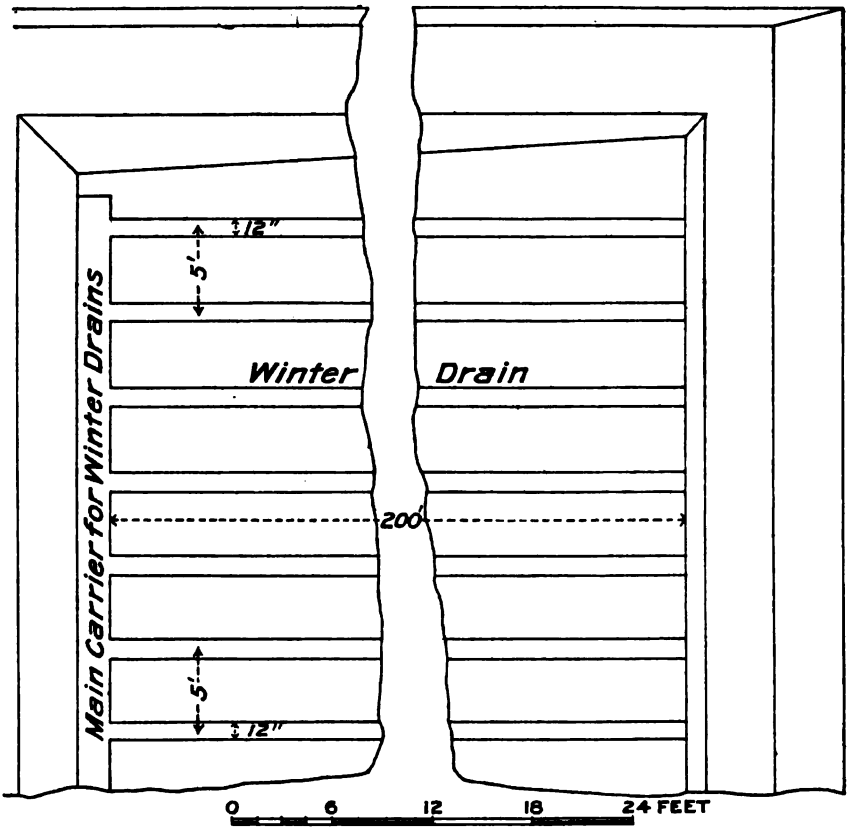


FIG. 15.—Plan of arrangement of winter drain on a filter area with absorption ditches.

In preparing intermittent filtration areas for the growth of crops level filter beds are made with low embankments around them, the area varying according to local conditions from 1 to 4 or 5 acres. Carriers are run on convenient lines for supplying sewage to these beds at suitable intervals. The area is also thoroughly underdrained, with the drains laid at least 5 feet deep. In some soils a slight advantage

will be gained by making the drains as deep as 6 or 7 feet. In order to grow crops upon such areas the surface is prepared with a series of absorption ditches, where the sewage is allowed to stand until it sinks away into the ground, the length of time required for its disappearance of course varying according to the permeability of the soil. Absorption ditches are illustrated by figs. 2, 3, and 15. On clean sands, as experimented with at the Massachusetts experiment station, it was found that very large doses of sewage would sink into coarse sands in a very few minutes, but in fine sands, especially after they had been a long time in use, the period is considerably prolonged. In some cases it may be as much as twenty-four hours, the depth of sewage applied of course entering in as a controlling element.

If it is desired to dispose of sewage on filtration areas fitted with

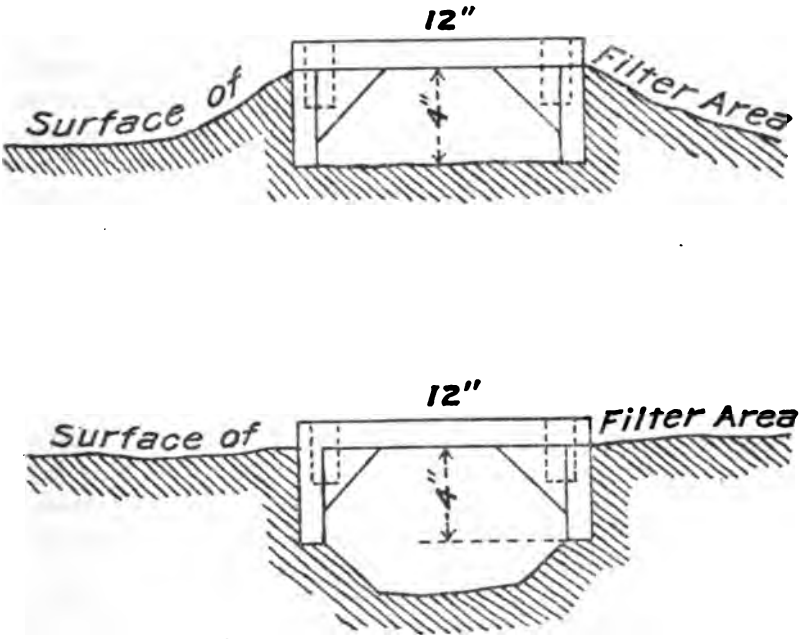


FIG. 16.—Cross section of winter drains.

absorption ditches during the winter season in extremely cold climates liable to heavy snowfall, and a high degree of purity of effluent is required, the ditches may be covered with boards, somewhat in the manner already described for the experimental sand-trench area at Lawrence. Where a lower degree of purity of winter effluent is sufficient, the areas may be left without any covering at all. Experience has shown that the sewage, by reason of reaching the fields at a temperature considerably above freezing, will penetrate beneath the snow, a film of ice freezing on the under side thereof and the process of filtration going on the same as if the snow were absent, except that the low temperature will tend to decrease the activity of the nitrifying organisms. This case, however, is provided for in a natural way. As shown

by the experiments, the tendency in winter is for the nitrogenous matter to store itself in the sand by what in effect is a process of simple straining. As warm weather comes on in the spring, nitrification again resumes its sway, with the result of finally resolving the stored matter of the cold period. We have here a very interesting illustration of the fine balance of forces sometimes existing in nature. The nitrifying organisms, by reason of susceptibility to temperature, are enabled to carry on their work more actively in warm weather than in cold. The soil, acting as a simple strainer, strains out the objectionable matters in cold weather and stores them up until the period of activity of the nitrifying organisms shall have again come round, when these minute agents again successfully perform their appointed work.

BEST CROPS FOR SEWAGE FARMING.

A large amount of study has been directed toward the question of the best crops for sewage farming, especially in England, with the result of showing that in that country, at any rate, almost any crop which can be raised in ordinary farming can be cultivated on properly managed sewage farms with good effect. Among the crops ordinarily raised we may mention Italian rye grass, seeds, pasture, potatoes, wheat, oats, barley, mangolds, carrots, cabbage, parsnips, turnips, beans, rhubarb, celery, peas, lettuce, and corn. In southern climates the yam has been grown to good effect with sewage irrigation, while in southern California, orchards are successfully irrigated with sewage. The species of water willow known as osier is also grown extensively on sewage farms, not only because it is a valuable crop in the vicinity of towns, where it is extensively used in basket making, but especially because it has the property of absorbing large quantities of water. The American water weed, anacharis, is also a very gross feeder and will assimilate large quantities of organic impurity. Among other water plants which are capable of absorbing organic impurities may be mentioned duck weed, sedges, common reed, flowering rush, water lilies, liverwort, water cress, etc. There is, however, no special advantage in using some of these so long as plants having commercial value can be raised.

At the Doncaster sewage farm in England, in addition to wheat, barley, oats, rye, potatoes, rye grass, clover, meadow grass, and osiers, considerable quantities of small fruits, such as currants, gooseberries, and raspberries, have been successfully cultivated. At Berlin the chief crops are rape grown for seed to be used in the manufacture of oil, colza, mustard, carroway, hemp, and the cereals—wheat, rye, barley, and oats—with potatoes, beets, turnips, cabbage, and vegetables generally.

In the irrigation on the Plain of Gennevilliers, at Paris, by reason of the nearness of the fields to the city of Paris, the crops produced are chiefly those common to ordinary French truck farming. As we

shall see farther on in discussing the Paris irrigation problem, very notable success has been attained here in the raising of all ordinary garden truck. Undoubtedly, however, the keeping of a large amount of live stock and the production of beef and dairy material is, on the whole, the most important branch of sewage farming. Italian rye grass in suited above all other grasses for irrigation, and in England, Scotland, and other countries yields, with sewage irrigation, prodigious crops of forage of best quality. Under favorable conditions it has yielded as much as 60 tons of green forage per acre per year. In an account of Italian rye grass which appears in Bulletin No. 73 of the North Carolina experiment station it is stated that Italian rye grass is scarcely hardy north of Washington, but is fully hardy in the Carolinas; that it resists drought well, but requires for the best results a deep, moist, rich soil. On poor soils it is stated to be of little value. The growth is upright, 2 or 3 feet high, and very leafy. On rich soils it should be cut every three or four weeks, as otherwise the heavy growth is apt to cause the grass to lodge and rot at the base of the culms. This grass shoots early in the spring and flowers in May. When grown for seed, it yields as much as 300 to 400 pounds per acre, worth from 3 to 5 cents per pound.

English perennial rye grass, the seed of which is quite similar to that of Italian rye grass, is also grown extensively in England, where it constitutes the chief grass of many of those famous pastures which have not been broken up or reseeded for over a century. It forms a very thick, compact turf, which is not easily broken by the feet of animals. This grass may be grown on the heavy clay soils of the South, but is not considered as fitted for the conditions of agriculture in the North.

The seed of the English perennial rye grass is much less expensive than that of the Italian rye grass, and hence is frequently used as an adulterant of the latter. The seeds of such weeds as are common to wet meadows are also frequently largely present in uncleaned samples of rye-grass seed. For these several reasons the Italian rye-grass seed should be purchased only of reputable dealers and under a guaranty of quality. A bushel weighs from 18 to 24 pounds. When sown alone, it requires from 45 to 50 pounds per acre.

Bulletin No. 73 of the North Carolina agricultural experiment station also states that Italian rye grass is one of the best grasses for temporary lays on good moist soil. It is best sown alone or with alsike clover. If sown in the fall, it will give five or six heavy cuttings in the succeeding year, and is best plowed up the next fall. If sown in the spring, it may be allowed to stand the second season. This grass has often been used in small quantities in mixtures to serve as a nurse for the less permanent and vigorous species, but it is now generally agreed that this is not the best practice, as the luxuriant growth of the rye grass is likely to smother out the grasses it was meant to assist. It

disappears at the end of the second year, leaving the ground unoccupied for weeds to come in. Italian rye grass is stated as very exhausting to the soil, and hence becomes especially amenable to irrigation by sewage. According to the experiments of the English Sewage of Towns Commission, as well as the practical observation of farmers who have tried it in the South in this country, its value for feeding is very high. When grown in the South, in ordinary farming, it is necessary to reseed it every second year; but probably with sewage irrigation it could be carried to the third year, the same as the ordinary practice in English sewage farming. At the Berlin sewage farm, where a considerable quantity of Italian rye grass is grown, the best mixture has been found to be timothy and rye grass, about half and half.

Clovers and alfalfa are also crops which have been found to thrive well on moderate sewage irrigation at different places, especially the latter. This will grow in favorable soil anywhere from about sea level to 7,000 feet elevation. It may be seen very commonly in the valleys under the foothills of the Colorado and California mountains. It grows best in a light, rich, sandy loam, underlain by a loose, permeable subsoil, and its development is considerably influenced by such conditions as the depth and warmth of the soil, the depth of the ground water below the surface, and the physical character of the subsoil generally. Its cultivation has been most successful in the arid regions of the West and Southwest, where, because of the light rainfall, an artificially controlled water supply is commonly used. Experience there indicates that it grows better under irrigation than under any other conditions, as in this way the quantity of water exactly suited to its best development may be supplied. Good drainage is necessary, as otherwise the plants are likely to be killed by an excess of water either in the soil or on the surface. When undergoing irrigation, water should not be allowed to stand on the alfalfa field more than forty-eight hours, as otherwise the ground becomes saturated and the plant liable to be drowned out. A very complete account of alfalfa may be found in Farmers' Bulletin No. 31 of the United States Department of Agriculture.

Before the modern application of the practice of ensilage to the preservation of green crops came into use one great difficulty in the management of sewage farms related to the disposition of the enormous green forage crops which sewage-irrigated land produces. With ensilage, however, this difficulty is entirely done away with, and sewage farming may be considered to have taken by its use a new impulse. Most of the reiterated objections of from twenty to twenty-five years ago as to the impossibility of operating sewage farms at a profit have been removed, and, indeed, ensilage is another recent new application through which sewage farming may be said to have taken on such entirely different lines of development as to render many of the discussions of an earlier date of little value.

In eastern countries silos have been used for preserving corn for many hundred years. Underground pits are stated to have been used by the wandering tribes of Arabia in order to prevent victorious enemies from obtaining possession of food supplies. The Moors brought the art of ensilage into Spain, whence it found its way into France and Germany, and finally extended to England and the United States, in which latter countries its use has mostly grown up since about 1880.

As to the theory of ensilage, it may be remarked that if green crops are left exposed to the air for any considerable space fermentation begins, and if left unchecked will continue until putrefaction sets in and the crop becomes useless for feeding purposes. It is now understood that fermentation is produced by the active agency of bacteria. According to the researches of Pasteur there are certain ferments which continue their action without the presence of oxygen; such fermentation is called putrefaction, and is accompanied by the production of bad odors. It is the opposite of nitrification, which takes place only in the presence of oxygen, and is, when working to the best advantage, entirely unaccompanied by odor.

Again, all putrefactive fermentation is accompanied by the production of considerable quantities of heat. If we place a green crop in the silo, but leave it freely exposed to the air for a few days, it becomes heated to a temperature of from 125° to 150° F., at which point the bacteria are killed and the subsequent fermentation which would otherwise have been produced by them is arrested. The material so produced is called sweet silage, which remains aromatic by reason of having gone through merely what is called hay fermentation.

When, however, the green crop is put into the silo and subjected to pressure, with the exclusion of air immediately after being put in, the temperature does not rise above about 100° F. At this point the bacteria are not killed and the fermentation proceeds to the point of forming lactic or acetic acids, the process being accompanied by the loss of some of the saccharine matters, which are supposed to break up and form new combinations, passing away partly as gas. This process produces what is known as sour silage, in contradistinction to the kind which is termed sweet. Cattle soon learn to eat either variety with avidity.

We will not take up space to describe the process of ensilage in this place, but simply refer the reader to Bulletin No. 32 of the United States Department of Agriculture, where very complete detail as to the construction and cost of silos, as well as to crops best suited to the process, may be found. We may remark, however, that the most common ensilage crop of ordinary farming in this country is Indian corn. Over a large part of the United States from 15 to 20 tons of clean fodder per acre can be grown without difficulty under the

conditions of ordinary farming. Considering the vigorous growths of Indian corn produced by sewage irrigation, it is probable that experience would soon show that on sewage farms from two to three times this quantity could be produced by growing, say, two crops on the same area in a season.[1]

In England the first experiments with rye-grass silage were made from ten to fifteen years ago, with the result of showing that there was no difficulty in preparing the rye grass for winter feeding in this way. At the present time ensilage is regularly used on nearly all the English sewage farms. Experience with it at the different farms will be given in the detailed accounts of the English sewage farms following.

As to the feeding value of sewage-grown grass, we may refer, for an authoritative exposition, to the reports of the English Sewage of Towns Commission. This commission experimented extensively on this subject and gave its report in great detail. Among other points presented, it shows that very large quantities of milk as well as beef can be produced from cattle fed on sewage-irrigated grass, and that the composition of the milk produced varied but slightly from that produced by cattle fed on ordinary unsewaged fodder. The milk from the sewage-grass-fed cattle was slightly less rich in casein, butter, and sugar than that from those fed on unsewaged grass.

In an experiment with oats, in which 135.5 gross tons of sewage were applied per acre, the gross value of the increased produce amounted to more than 10 cents per ton on the sewage employed; in another experiment, in which 510 gross tons of sewage were applied per acre, the gross value of the increased produce amounted to 3 cents per ton of sewage employed.

In the immediate vicinity of towns, where garden truck can be conveniently disposed of, truck farming will necessarily be an important branch of this special department of irrigation. When, on the other hand, the sewage farms are for any reason situated farther away from towns, dairy farming and the raising of cattle will become the leading branches, the cattle being fed on green forage during the summer and on stored roots, such as mangolds, beets, swedes, etc., and rye grass and corn silage in the winter. Working intelligently on these lines, it is believed that a fine profit can be realized from such farming in almost any locality.

QUANTITY OF SEWAGE TO BE APPLIED.

As to the quantity of sewage which may be applied per acre, the experiments of the Sewage of Towns Commission indicated varying amounts ranging from 400 to 500 gross tons per acre per annum on

[1] For literature of ensilage as applicable to American conditions, see Sewage Disposal in the United States, pp. 257-259.

heavy land in wet seasons on ordinary crops to about 9,000 tons per acre on grass plots.

As we have seen, the daily average sewage in this country will probably be at least 80 United States gallons per head, giving the annual amount of sewage per capita at 97 gross tons. On this basis the range of application per acre would vary from the sewage of 5 to that of 93 persons. Include some additional sewage which land may be expected to clarify without reference to the results of cropping, and we may take from 50 to 150 persons per acre per year, though the quality of the soil may be expected to materially influence the result. We may point out, however, that with intermittent filtration areas, provided by the towns for the purpose of purifying sewage when not needed in agriculture, the question of number of inhabitants per acre from which the sewage may be utilized has little significance further than as a guide in estimating the probable quantity of sewage which each farmer may be expected to require in ordinary seasons. For completion of our subject we may give in detail the statistics of the quantity of sewage utilized on a number of the foreign farms, drawing for our information upon the paper, "Notes on European practice in sewage disposal," by Charles S. Swan, M. Am. Soc. C. E., to be found in Volume VII of the Journal of the Associated Engineering Societies.

From the tabulations there given it appears that at the Croydon Beddington farm, with a gravelly soil, the volume of sewage used in broad irrigation may be as great as 3,860 cubic feet per acre per day, which amounts to an average depth of sewage on the area per annum of 32.3 feet. At Doncaster, with sandy or gravelly soils, the average application is 395 cubic feet per acre per day, amounting to a total depth on the area of 3.31 feet per annum. At Leamington, with a soil mostly gravel, the average application is 546 cubic feet per acre per day, amounting to a depth of 4.6 feet on the area.

At the Berlin Malchow farm, with a heavy soil, the average application ranges from 288 to 346 cubic feet per day, amounting to a total depth on the area of from 2.4 to 2.9 feet. On the Berlin Falkenberg farm, with a heavy soil, the average application is 483 cubic feet per acre per day, amounting to an average depth over the area of 4 feet. On the Berlin Osdorf-Grossbeeren farms, with sandy soils, the average application is from 616 to 640 cubic feet per acre per day, amounting to a total depth for the area of from 5.2 to 5.4 feet.

At the Paris Gennevilliers irrigation area, with sand and gravelly soils, the market gardeners apply about 1,305 cubic feet per acre per day, which amounts to 10.9 feet over the area per year. On this point attention is called to the account of irrigation at Gennevilliers on pages 93–98. In filtration without cultivation, as carried on at Gennevilliers, 3,616 cubic feet per acre per day, or a total depth of 30.3 feet per annum over the area, have been applied. The maximum limit at Paris with sandy and gravelly soils was formerly 3,915 cubic feet

per acre per day, which amounts to 32.8 feet depth over the area, but during the last few years even larger quantities have been applied.

THE LIMIT OF TEMPERATURE.

Question is frequently raised as to the temperature limit at which the purification of sewage by either broad irrigation or intermittent filtration can be carried on, and widely varying opinions have been expressed. The last few years, however, have furnished a considerable amount of data on this point, which enable one to form more definite opinions than were possible formerly. If one takes a map of the United States on which the mean winter temperatures at the principal cities are laid down, it will be seen that the curve of 32° mean January temperature (January is taken as being the coldest month) passes between New York and Philadelphia, just south of Columbus and Indianapolis and St. Louis, and just north of Cincinnati. It also passes to the south of Dodge City, Kansas, and to the north of Oklahoma; passes south of Santa Fe, New Mexico, and thence curves north through the State of Nevada and a little to the west of Winnemucca. The curve passes about through the middle of the State of Washington. It may be assumed without discussion that at all points south and west of this line the temperature difficulty will never appear in connection with sewage purification by the land process.[1]

To the north of the line, however, we may define a strip of country the northern limit of which is between Boston and Portland, and to the north of Albany and Oswego, Rochester, Buffalo, Detroit, Grand Haven, Chicago, Keokuk, Dodge City, Denver, and Salt Lake City, within which limits, with proper management, sewage purification by the land process may be carried on in winter without serious difficulty. In the portion of the United States north of this latter limit, probably, special appliances would be needed for a successful winter purification. These conclusions are based upon a study of sewage as received at purification works in winter in comparison with soil temperatures at various depths, as kept at a number of sewage farms, as well as at the agricultural experiment stations in this and other countries.

Our first important fact is that the mean temperature of sewage is much higher than that of the air. At Lawrence, in January, 1888, the mean temperature in the main sewer was 46.5° F. The mean temperature of the air in January was 15.46° F. In 1889 the mean temperature in the main sewer was 45.9° in January, while the mean temperature of the air was 31.40°. Similar differences of temperature as between the sewage and the air are found to exist in other places. This considerable difference between the temperature of the sewage and of the air is sufficient to not only prevent the sewage from

[1] For map illustrating the foregoing in regard to temperature curve, see Allen Hazen, Filtration of Public Water Supplies; New York, 1895.

freezing readily, but to keep the ground itself open and free from frost. In regions of large snowfall the sewage passes under the snow, forming a crust of ice on the under side, and the irrigation goes on through the unfrozen soil the same as when snow and low temperature are absent. The difference in the degree of purification attained has already been discussed in the foregoing pages.

As to how the sewage retains sufficient heat to prevent freezing of the ground, we have to consider that water not only parts with its latent heat very slowly, but even after the freezing temperature of 32° F. is reached every pound of water still contains 142 heat units, which must be entirely withdrawn before a given pound of water can become frozen solid. Another reason why a body of water which is continually receiving accessions of water at considerably higher temperature than the mean of the body will freeze with great slowness may be found in considering that after the formation of an ice cover the loss of heat from the water is still further retarded by the condition that it can then take place only by conduction through the ice cover, which has a low rate of conductivity, thus leading to still further retardation in the process of loss.

The quality of the material of which filter areas are formed will, however, influence somewhat the rate of loss of heat in cold weather. According to the classical experiments of Schubler on the physical properties of soil, it appears that the relative power of retaining heat varies greatly in different soils. According to his experiments, lime sand required three hours and thirty means to cool from 145° to 70° F.; clay loam cooled between the same limits in two hours and thirty minutes; heavy clay in two hours and twenty-four minutes; pure gray clay in two hours and nineteen minutes; garden soil in two hours and sixteen minutes; humus in one hour and forty-three minutes, while water required thirty hours and seven minutes in cooling from 145° to 70° F. The conditions were the same for all of these materials.

Schubler's experiments also show that black soils retain their heat better than those which are white and light colored, and that this property resides almost wholly in the surface. A practical application of this fact may be made by constructing the broad surface of artificially prepared filtration areas of dark-colored sands or gravels.

Temperature observations as made at the Berlin sewage farms show that the mean of the soil temperatures there is considerably above that of the air. The same fact has been, generally speaking, brought out by an extensive series of soil temperatures taken at the various agricultural experiment stations in this country, although there are exceptions, which, however, do not invalidate the general proposition.

Without presenting the full information upon which these deductions are based, we may say that generally at a locality with a mean

air temperature for the coldest winter months not lower than about 20° to 25° F., and with sewage distributed to a purification area at a temperature not lower than about 45° F., purification by the land process may be effected without serious interruption from frost, the winter purification being, as already pointed out, less than that realized in summer. If the mean winter temperature falls for any considerable length of time much below 20° to 25° F., there will probably be trouble from frost. By reason, however, of the facility with which the level embanked areas of the filtration process may be operated as continuous filters during extreme cold weather, it is probable that the filtration process, pure and simple, may be operated at a somewhat lower temperature than the broad irrigation process. As a safe limit, the lowest mean air temperature for filtration may be set at from 18° to 20° F.

The foregoing statements as to practicable mean winter temperatures are to be considered, however, in relation to the quality and temperature of the soil used. Before deciding as to just what can be reasonably expected in a given locality, therefore, one should have at hand a statement of the physical properties of the soil as well as the mean temperatures of the coldest months. As repeatedly pointed out, sandy soils are preferable for both irrigation and intermittent filtration. As regards temperature, this preference arises not only on account of their open texture, but because they possess greater capacity for heat. The great desideratum of successful sewage purification in winter is a medium which will prolong the time of congelation. It is considered that sand answers to this requirement better than any other material.[1]

COST OF LABOR ON SEWAGE FARMS.

When examining a number of the best-managed sewage farms of England in the fall of 1894, the author was much surprised to learn that, generally speaking, somewhat higher wages are paid on sewage farms than on farms of the same character in the immediate neighborhood, and one reason why he is now of the opinion that sewage farming may be made commercially profitable in the United States is derived from the consideration that the wages actually paid for labor on many of the English farms are quite as high or even higher than the present rate of wages for farm labor in many parts of this country.

As regards a comparison, therefore, between the English sewage farms and American conditions, the frequently urged objection that we could not afford the large amount of labor required here certainly has no weight. In order to present this phase of the question in

[1]The reader wishing to go extensively into the rela tions of temperature to winter purificatin should consult Chapter XVII of Sewage Disposal in the United States, on "The temperature of the air and of natural soils, and its relation to sewage purification by broad irrigation and intermittent filtration," where an extended discussion may be found.

some detail, the author is enabled, through the kindness of Mr. S. S. Platt, Assoc. Mem. Inst. C. E., borough engineer at Rochdale, England, to include the following statements as to the actual prices paid during 1895 at a number of the English sewage farms. This information was gathered by Mr. Platt directly from the managers of the several farms:

At Birmingham, with an area of 1,300 acres, 222 men, 14 women, and 22 children were employed as an average during the year 1895. The men received 21s. per week, the women 10s., and the children 8s. On similar farms worked by ordinary methods in the neighborhood men received, in 1895, 16s. per week, women 9s., and children 6s.

At the Burton-on-Trent farm, with an area of 575 acres, the force employed consists of 4 wagoners, at 20s. each per week; 3 cow men and a shepherd, 19s. per week; 24 ordinary laborers, at 17s. per week, and 7 laborers attending to the sewage distribution, at 23s. per week; 2 foremen, at 30s. per week, one of them being furnished with a horse in addition; 1 weigh clerk, at 20s. per week; 2 men with steam cultivator, 1 at 27s. 6d. per week and 1 at 21s. per week. Four boys are also employed, 1 at 4s. per week, 2 at 7s. per week, and 1 at 9s. per week.

At the Crewe sewage farm, with an area of 269 acres, the average labor consists of 20 men, receiving from 14s. to 21s. each per week. On ordinary farms in the neighborhood of Crewe common labor receives from 14s. to 16s. per week.

At Croydon, with a total area of the two farms of 630 acres, the labor employed is as follows: One man at 32s. per week, 1 at 30s., 1 at 27s., 2 at 26s., 2 at 25s., 12 at 24s., 2 at 23s., 1 at 22s. 6d., 8 at 21s., 5 at 20s., 1 at 19s. 6d., 18 at 18s., 3 at 17s., 4 at 16s., 2 at 15s., 2 at 14s., and 1 at 13s. 6d. The total number of men employed at Croydon is found to be 68, and the average weekly wage is 19s. 10d. per week. On ordinary farms in that vicinity the wages of common laborers range from 18s. to 20s. per week. Carters receive 23s. per week.

At West Derby, with an area of 207 acres farmed, the labor varies from 22 to 40 men, according to the season, the wages paid ranging from 10s. to 24s. per week. On ordinary farms in the vicinity about the same rates are paid. The head foreman receives 30s. per week, together with free use of a cottage, garden, and coal. Six of the regular farm hands are also furnished with cottages and garden free.

At Northampton the total area farmed amounts to 688 acres, the labor including about 50 men, 25 women, and 12 boys. The wages paid are from 15s. to 18s. per week for the men, 10s. for the women, and from 5s. to 10s. for the boys. On ordinary farms in the neighborhood the wages range about 1s. per week less.

At Nottingham the total area farmed amounts to 908 acres, requiring from 40 to 50 men and from 15 to 20 boys. The men receive from 14s. to 17s. per week wages, and are also furnished with good houses

and large garden, rent free. Manure and seed potatoes are also furnished free. The boys receive from 4s. to 10s. each per week. On ordinary farms in the neighborhood men receive 12s. to 15s. per week, without house and garden, and boys about 1s. less per week than on the sewage farm. On the sewage farm all the men employed are paid extra for overtime and are allowed harvest piecework at the same rate per acre as strangers who are not found houses.

At Oxford the total area farmed is 370 acres; the amount of labor fluctuates from 15 to 30 men, according to the season, together with 2 women and 4 boys. The men receive from 12s. to 15s. per week, women 6s. per week, and boys from 3s. to 5s. per week. On ordinary farms in the neighborhood men receive from 11s. to 12s. per week and women 6s. per week.

At Tunbridge Wells, on the north farm, consisting of 191 acres, 1 man is employed flowing sewage at £1 per week and cottage, 5 laborers at 16s. and cottage, 1 laborer at 16s. per week without cottage, and 1 boy at 10s. per week. On the south farm, which consists of 199 acres, 1 man is employed flowing sewage at £1 3s. and 6d. per week and cottage, 4 laborers at 16s. 6d. per week and cottage, 1 laborer at 19s. per week without cottage, 3 at 15s. per week without cottage, and 1 boy at 9s. per week.

At Warwick, with an area of 134 acres, 10 men are employed at 15s. per week and cottage. On ordinary farms in the vicinity the laborers receive from 10s. to 13s. per week.

At Wimbledon, with an area of 70 acres, the labor varies from 3 to 8 or 10 men, depending upon the season. The price of labor ranges from 21s. to 30s. per week, at which prices it is stated that the very best men of the vicinity are obtained. The amount expended in wages on this farm during the year ending March 31, 1896, was £639 3s. 2d.

At Wolverhampton, with an area of 600 acres, the labor amounts to about 22 men and 3 boys, the men receiving from 18s. to 20s. per week, and the boys 6s. Laborers on ordinary farms in the vicinity receive about the same price.

Relative to the cost of management on a number of the leading English sewage farms, we may refer to a return showing the salaries and emoluments of sewage-farm managers, etc., as contributed by Joseph Gordon, Mem. Inst. C. E., borough engineer at Lester, which may be found in Volume XV of the Proceedings of the Association of Municipal and Sanitary Engineers and Surveyors. From this return it appears that at Birmingham the management of the farm is in the hands of a general manager or superintendent, who receives a salary of £350, with use of horse and wagon. At Burton-on-Trent the manager receives a salary of £150 per annum; at Crewe, a salary of £160 per annum. At Croydon the manager of the Beddington farm receives £220, with house and gas provided. The manager of the Croydon Norwood farm receives a salary of £156. At Northampton the manager

receives a salary of £250, and is furnished in addition thereto with house and garden and horse and wagon.

At Nottingham the management is in the hands of the farm bailiff, who receives a salary of £300 per annum.

At Tunbridge Wells there are two farm bailiffs, who each receive a salary of £120 per annum with house and garden and the produce of a cow.

At Warwick the farm is managed by a superintendent, under the direction of a committee, who is paid £120 per annum.

At Berlin, as stated by Mr. Roechling in his paper on "The sewage farms of Berlin," which may be found in Volume CIX of the Proceedings of the Institution of Civil Engineers, the labor of the sewage farms is largely performed by misdemeanants; that is, by men sent for various minor offenses to the city house of correction. In 1890 the total number of misdemeanants employed on the Berlin sewage farms amounted to 737, their labor costing the sewage farm about 13 cents each per day. Besides this number of misdemeanants a large number of free laborers were employed on the farms at an average price of about 40 cents per day. By observation it has been concluded that the work performed by two free laborers at this price is fully equivalent to that of seven of the misdemeanants. At this rate it is clear that from a pecuniary point of view there is no saving to the farm management from the employment of the misdemeanants, as, at the rates mentioned, the labor done by misdemeanants at a cost of 91 cents per day is performed by free laborers at a cost of 80 cents per day. There is, however, a decided advantage to the administration of the house of correction, which is also owned and managed, as well as the sewage farm, by the city authorities. As a matter of philanthropy Mr. Roechling says the employment of the misdemeanants may be also highly commended, as it gives the men a chance to acquire regular habits while undergoing their punishment.

In considering the significance of the price of labor paid in England and in Germany in its application to American conditions, it must be remembered that in England the price of the ordinary crop sent to market from the sewage farms will compare with the prices prevailing in the United States very much in the same way and in the same ratio as that which obtains between the price of labor in the two countries. In Germany, on the contrary, where labor is considerably lower, the prices of produce are also lower, all of which must be taken into account in drawing conclusions as to the possibilities of establishing sewage farms here. In France the price of labor does not vary greatly from the price in Germany.

SANITARY CONDITION OF SEWAGE FARMS.

There has been much discussion at various times as to the sanitary condition of sewage farms, and formerly much apprehension was expressed as to the possibility of contaminating not only the well

waters of the surrounding areas, but also the atmosphere in the vicinity. As to the contamination of well waters, the development of a clear understanding of the actual facts in regard to nitrification has gone a long way toward relegating this particular objection to sewage farming to the region of exploded objections, which, as we have seen, is now occupied by a large array of the arguments of the opposition as advanced from twenty to twenty-five years ago. At the Berlin sewage farm the effluent is so pure that it can be admitted into any water course, and can not be distinguished by the senses from the clearest spring water.

In order to obtain information as to the extent to which sewage farming may affect the health of the inhabitants of the farms, the Berlin authorities have established a system of registration of all cases of sickness and death. The following facts bearing upon the sanitary condition of the farm are derived from Mr. Roechling's paper already referred to. The average annual population to which the figures apply was, during the five years from 1885 to 1889, 1,580, of which 986 were men, 285 were women, and 327 were children under 15 years of age. The 958 adult male population included 850 misdemeanants, who were probably impoverished in health by irregular habits of life. The records show that the death rate per 1,000 from all causes was 11.24 in 1885, 9.22 in 1886, 14.83 in 1887, 6.79 in 1888, and only 4.81 in 1889. Of the total deaths, 16 per cent were men, 9 per cent women, and 75 per cent children, the mean rate of the whole five-year period being 9.75. The death rate from the seven principal zymotic diseases, smallpox, scarlet fever, diphtheria, typhoid fever, measles, whooping cough, and diarrhea, was 4.32 in 1885, 3.69 in 1886, 4.15 in 1887, 1.13 in 1888, and nothing in 1889, the mean rate during the period from these causes being 2.53. The period covered by these statistics is, of course, too short for definite conclusions to be drawn, although it may be stated that the same low rates have continued until the present time. If, however, statistics mean anything, they indicate clearly that the conditions of this farm are not in any degree unhealthful. It may also be stated that drinking water for use on the farms is obtained by wells sunk at the points where water is required. With one exception there has been thus far no indication of any trouble with these wells. The reports also show that the sewage farms do not exert any detrimental effect upon the health of cattle kept upon them or on the adjoining farms. At Berlin it is even said that the small sickness which has occurred among the cattle has been imported.

The question of the sanitary conditions of sewage farms was examined at length by a committee appointed by the Royal Agricultural Society in the sewage-farm competition of 1879, to which we have referred. This committee concluded that sewage farming is not in any degree detrimental to life or health. Statistics presented by it show that the rate of mortality, on an average, for the number of years

that the farms considered had been in operation does not exceed 3 per cent per annum, the result comparing favorably with that obtained somewhat more recently at Berlin.

We are obliged to conclude, therefore, that properly managed sewage farms are not detrimental to health.[1]

NUMBER OF BACTERIA IN SEWAGE-FARM EFFLUENTS.

By way of showing the degree of bacterial purification effected by sewage farms we may refer to the following observations made by Prof. E. Ray Lankester on the sewage and effluent of the Oxford sewage farm, England, and the water of the Oxford River, into which the effluent from this farm discharges. These observations were made on the given dates in the summer of 1892.[2]

Comparison of number of bacteria in sewage and in river near Oxford, England.

Sample from—	Bacteria per cubic centimeter.					
	June 27.	July 21.	July 28.	July 29.	September 11.	October 5.
Sewage	648,000	12,000,000	1,688,000	1,688,000	528,000	2,486,000
Effluent	42,000	20,500	60,000	60,500	27,000	27,000
River above effluent	1,020	4,700	14,300	24,300	1,800	2,000
River below effluent	900	11,000	24,900	24,900	9,072	14,580

Professor Lankester states that the most important fact brought out by these studies was that the species of bacteria which belong characteristically to sewage (*B. coli communis*, etc.) were not found in the sewage, but only fluviatile species. He further states that it may be asserted in a general way that the effluent contains no more bacteria, nor other kinds of bacteria, than are to be found in other streams draining from agricultural lands in the neighborhood.

SEWAGE FARMING IN ENGLAND.

Having taken a rapid review of the general subject of sewage irrigation, it is now in order to briefly describe a few of the more notable examples of sewage farming abroad and in this country. First may be considered the English farms, and then, briefly, those of Germany and France. Five examples are given from England typical of prevailing conditions, these being the Croydon Beddington farm and the Leamington, Birmingham, Wimbledon, and Doncaster farms. There

[1] See paper by Dr. Alfred Carpenter, of Croydon, read before the British Medical Association in 1888. Dr. Carpenter lived for many years in the immediate vicinity of the Croydon Beddington farm.

[2] Statement by Prof. E. Ray Lankester to the Royal Commission on Metropolitan Water Supply, Appendix C, 61.

are probably more sewage-purification works in England than in any other country, but they all present merely variations in details.

In regard to the present views of English engineers, sanitarians, and sewage-farm managers, it may be stated that the consensus of opinion, as it appeared to the author in 1894, was decidedly in favor of the land purification process. If for any reason it is necessary that the effluent from sewage-purification works should pass into a stream which is the source of a water supply, the further consensus of opinion appeared to be that it should, before receiving the land treatment, be clarified to the extent of removing all of the suspended and a small portion of the dissolved matter by some of the more inexpensive chemical processes. The same views, it is believed, are now held in the United States by many competent engineers, although the effluents from high-grade intermittent filtration areas are also unobjectionable.

CROYDON–BEDDINGTON FARM.

Croydon Borough is a suburb of London, with a stated total population of about 115,000 to 120,000, the daily flow of sewage amounting to an average of 4,500,000 gallons. In addition to the Beddington irrigation farm the borough has another farm at Norwood. The area at Norwood is stated at 105 acres and that at Beddington 525 acres, making a total area of 630 acres, of which about 525 acres are actually under cultivation. Inasmuch as the Beddington farm is the more interesting of the two, we will confine our description entirely to it. At Beddington 425 acres are in irrigation, the balance of 100 acres being occupied by the farm buildings, cottages, roads, and the ground too high to be reached by the sewage, which is delivered upon the farm by gravity. The buildings upon the Beddington farm include 4 farmhouses, superintendent's residence, and 14 cottages. This farm was designed and laid out by the eminent English sanitary engineer, Baldwin Latham. When irrigation first began, in 1860, the original area was much less than at present, additions having been made from time to time to accommodate the growth of the town and consequent increased flow of sewage.

A considerable portion of the soil is an open, porous, black loam from 6 to 10 inches in depth, with occasional areas of a light, free, open soil, but all suitable for irrigation. The subsoil is gravel and sand. The farm has a gentle slope from east to west averaging from 1 in 150 to 1 in 250. The River Wandle flows to the south and west of the farm. The first underdrains were laid under a portion of the farm about fifteen years ago. They have been laid wide apart, and in some cases as much as 9 feet in depth; conductors vary from 4 inches to 2 feet. The chief value of these drains is that they help to dry the land out quickly after the sewage is taken off.

The slope of the soil of this farm is so uniform that about the only

preparation required was a slight adjustment of the surface by raising at some places and lowering at others, but so little of this as not to cut through the top soil. The main carriers along the higher portions of the farm are usually of concrete about 3 feet wide, and level or nearly level where the ground permits. The secondary carriers are also in some cases of concrete. The small distributaries are made with a plow, a furrow being laid from the secondary carriers down the line of greatest descent and at a distance from each other of from 40 to 50 feet, in order to flow the sewage over all portions of the area to be irrigated. Heavy galvanized-iron or wooden stoppers are used at varying distances down these trenches. For this work, when the field is undergoing irrigation, a man passes over and places the stops at each

FIG. 17.—Outdoor ensilage of rye grass at Beddington.

point as needed. On the lower side of each field there is a collecting ditch, into which the effluent water passes. The arrangement of the farm is such that the effluent of the first irrigation is passed over the fields a second time, and, when necessary, a third time. In this way very efficient purification is attained. The time occupied in passing through three irrigations is stated at from three to four hours. As to the loss of water from irrigation, the general statement is made that about 2 out of every 3 gallons of sewage passed onto the farm flow off as purified effluent, the third gallon having been either evaporated or absorbed by the land or growing crop.

The principal crops raised are Italian rye grass, pasture, mangolds, and other root crops, osiers, cereals, and cabbage. Rye grass, the principal crop, is stated to exhaust itself on this farm in about three

years, when it is followed by a crop of mangolds, cabbages, or wheat and oats, with a return after that to rye grass. Five or six cuttings of rye grass are grown in a season. Mangolds yield especially well here. Wheat and oats are grown chiefly for the straw. Enough horses are kept for working the farm. About 200 milch cows are also kept for the purpose of consuming the large quantities of rye grass and roots grown.

As to the purification effected at Croydon, no analyses appear to have been made in recent years. From a series made after the farm had been in operation for about ten years it is concluded that the purification attained then was very efficient.

This farm was visited by the author on October 20, 1894. At that time of year the main crops had been removed, although fine fields of cabbage and mangolds were still standing, and a casual glance at them indicated the successful results in sewage utilization obtained at this farm. The last cutting of rye grass of the season was in progress at that date, and in one field an outdoor rye grass ensilage stack was in process of making, as illustrated by the photograph, fig. 17. Several pasture and cut rye-grass fields were under irrigation, the sewage coming onto the same black and filthy, and absolutely without any preliminary straining or purification. The first irrigation showed marked improvement; the second showed still more improvement, and, finally, after the third, the effluent flowing in the ditches appeared as bright and sparkling as any stream of water flowing from agricultural lands. The floating matters of the sewage are stated to have never given any trouble on this farm.

Mr. Greenwood, the farm superintendent, stated that 100 acres additional had just been purchased, and it was contemplated to purchase about 50 acres more in the spring, making the total area of the farm when this is done about 675 acres. During the year 1893 the farm is stated to have paid £3,000 more than all cost of operation, not including, however, interest on first cost.

As to the cost of laying out this farm, it may be remarked that by reason of the use of concrete carriers and distributaries the first cost was higher than would now be considered necessary. At the present time the laying out of the farm could be accomplished for somewhat less than the actual cost when done thirty-seven or thirty-eight years ago.[1]

There are a number of country houses along the highways leading through or at the sides of this farm. The author was accompanied on his visit by Lieut. Col. Alfred S. Jones, V. C., a well-known English sanitary engineer, whose residence is on the banks of the River

[1] This is not intended as in any degree a criticism on the work of Mr. Latham. In 1858-1860, when this farm was laid out, we had much less knowledge derived from experience in sewage irrigation than at present. Probably the leading idea was to make permanent work, and from this point of view the work must be considered very successful. Since 1860 we have learned that sewage can be distributed in ordinary earth channels equally well, thus not only materially decreasing the first cost, but rendering it easier to realize a profit on sewage-farm investments as well.

Wandle, near the point where the effluent from the Beddington farm enters that stream. In the course of a walk about the farm, a stop was made at the residence of a gentleman whose garden plat of 3 or 4 acres is surrounded on three sides by the irrigation fields of this farm. As to the question of nuisance, the owner stated that no nuisance had ever been created by the sewage irrigation that he had considered in any degree objectionable, although there were occasionally slight smells in warm weather. When the place was first occupied by him, over twenty years ago, he had rented, but on the expiration of the lease he had bought the freehold of the property, because it suited him, and he had not considered in making such purchase that the value of the property was in any degree injured by the presence of the sewage farm. He also said that a neighboring cow yard, where a considerable number of cows were kept for the purpose, as already stated, of feeding sewage-grown produce, was regularly a source of much more serious effluvium nuisance to the neighborhood than ever came from the farm itself. At the time of the author's visit, in October, absolutely no smell of any sort could be detected in any part of the irrigated fields.

The statement was made that no difficulty with the irrigation had ever been found here in the severest cold weather. Ice forms on the surface, but the sewage flows underneath it, sinking away into the ground, and the purification still going on, although probably a larger area is required in winter for a given purification than in warm weather. As one of the model English sewage farms, the Croydon Beddington farm has been frequently described.[1]

LEAMINGTON FARM.

In the Royal Agricultural Society's sewage farm competition, to which reference has already been made, one of the prizes awarded was to the sewage farm at Leamington Springs, which is owned by Lord Warwick. This farm was visited by the author on October 25, 1894.

The borough of Leamington Springs has a stated population of 27,000, although there is considerable variation in the population, owing to the large number of visitors during the season. The sewage is delivered by the borough upon a farm of about 400 acres, owned by the Earl of Warwick, at a distance from the borough of about 2 miles. The borough receives £300 per year for the sewage, and its responsibility ceases when the sewage is delivered at the point agreed upon on the farm, which is at an elevation of about 131 feet above the pumping station. In the agreement it is stipulated that the effluent from the farm shall be purified to the satisfaction of the conservancy commission of the River Leam, into which it finally flows.

[1]See Crimp's Sewage Disposal and Rawlinson and Read's Report on Sewage Disposal as made for the Local Government Board in 1876. An extended series of analyses of the sewage and effluent not only of this farm but of the Croydon Norwood farm may be found in this report.

The present flow of sewage in wet, rainy weather is about 800,000 gallons per day. In dry weather it is somewhat less. The sewage is to be pumped only between sunrise and sunset, except that in the winter months pumping may begin one-half hour before sunrise and continue to one and one-half hours after sunset. In order to take care of the flow of sewage during the night a storage tank is provided at the pumping station of about 1,250,000 gallons capacity, or enough to hold more than one day's flow, which receives the night flow and also provides for contingencies.

The farm is under the charge of Mr. Castle, as farm bailiff, who stated that the farm operations had been in every sense commercially successful. As a matter of business caution he declined to state just what profits had been obtained, but intimated that in no year were

FIG. 18.—Field of cabbage at Leamington.

they less than 8 per cent. The crops raised are rye grass, roots, cabbages, wheat, oats, and barley. The grains are sown in rotation after roots and cabbages, and are not themselves irrigated at all, the heavy irrigation of the preceding crop of roots being relied upon to support the grain crops. About 150 head of cattle, mostly thoroughbred shorthorns, are kept upon the place, and a large amount of milk is sold, this being considered of superior quality. There are also about 10 acres of fruits which are irrigated lightly. The topsoil of the farm is black and porous, with a gravelly subsoil at from 12 to 15 inches below the surface.

One of the most interesting points learned on this farm was in regard to the process of ensilage. Mr. Castle stated that they had for

several years made rye-grass ensilage both in silos and in stacks in the field and had been entirely successful in both ways. The most of the silage is made sweet or without salt, but in order to make sweet silage with the best results it is necessary that the silo be filled very quickly, or if stacked that the stack be completed and weighted within one day, before any heating begins. The statement was also made that during 1893 a cubic foot was cut out of one of the silos and found to weigh 57 pounds, at which rate a cubic yard would weigh 1,539 pounds.

Sewage is delivered to the different parts of the farms in a few lines of main carriers of vitrified tile, which deliver it at convenient points into wells provided with gates, from which it flows out into distrib-

FIG. 19.—Stacks of sewage-farm wheat at Leamington.

uting carriers and from there into the secondary distributaries laid on the contours, and is thence flowed over the land by spade gates after the usual manner. The standing crops of roots and cabbages were very fine and spoke well for the thoroughness of the cultivation, as well as the efficiency of sewage irrigation as practiced on this farm. The effluent before leaving the farm is passed over a field of osiers, whence it flows into the River Leam bright and sparkling.

The following details in regard to the cropping at Leamington have been obtained from the report of the Royal Agricultural Society's committee, made in 1879:

Rye grass is grown both for sale and for home consumption. It is not allowed to stand longer than two years, and about 25 acres are sown each year, usually in the autumn, at the rate of 3 bushels of seed per

acre. A crop sown in September, 1877, was cut eight times in 1878 and six times in 1879, and then plowed up. In 1878 the cutting of rye grass commenced on February 2. In 1879 that sown in 1878 was first cut April 7. The first cutting yielded 4 tons per acre of green grass; the second cutting, June 4, yielded 16 tons of grass per acre; the third cutting, on July 8, 14 tons of grass per acre; the fourth cutting, August 14, 8 tons; the fifth cutting, September 14, 6 tons; the sixth cutting, October 6, 5 tons; and the seventh cutting, in November, 2 tons per acre, giving a total yield of 41 tons of green grass per acre for the year.

Mangolds are also grown largely on this farm. The seed is drilled in rows 26 inches apart and the plants are hoed out to 10 inches distance in the rows. The sewage is not applied until the plants begin to bulb, when they are irrigated. In 1878 this crop received 21 dressings of sewage while under cultivation, or 8,265 tons of sewage per acre, equivalent to an irrigating depth of 81.8 inches of water in addition to the rainfall.

Ordinary cabbages for market are planted on the level in rows 22 inches distance and the plants 17 inches apart in the rows. The cabbages are irrigated during the period of growth. In 1878 one field in this crop received 17 dressings of sewage, amounting to about 6,102 tons, equivalent to an irrigating depth of 60.4 inches in addition to the rainfall. Parsnips are grown on the level, 6 pounds of seed per acre, drilled in rows 14 inches apart and hoed out 6 inches in the row. The crop is not irrigated, but usually succeeds cabbage or second-year rye grass which has been sewaged.

Carrots are drilled in rows on the level at 14 inches distance and are hoed out to from 4 to 6 inches in the rows. Six pounds of seed per acre are sown. The crop is not directly irrigated with sewage, but, like parsnips, succeeds, either directly or after a second year, a crop that has been heavily dressed with sewage.

Potatoes are planted in drills 24 to 26 inches apart and 12 inches from plant to plant in the rows. They usually succeed rye grass which has been cut the full number of cuttings the previous year. Potatoes are not directly sewaged during the period of their growth. Rhubarb is one of the permanent crops at Leamington, as well as elsewhere. It costs about £50 per acre to purchase roots, prepare the ground, and plant out, and the crop is stated to realize about £40 per acre per year. The plants are irrigated with sewage during the period of growth.

A large acreage of wheat is grown on the farm, but as a rule not under the influence of sewage. Generally the wheat follows some crop which has been heavily sewaged. A considerable quantity of oats is raised, and they generally yield well. This crop, like wheat, is not directly irrigated, but usually succeeds rye grass. Barley is also grown, but not with direct sewage irrigation, following, the same as the others, crops which have been heavily irrigated.

Large quantities of beans are grown as part of the miscellaneous production, and which are not directly irrigated with sewage. They usually follow some root crop or cabbage.

Turnips and swedes are also grown on this farm. Green crop turnips are sown broadcast, about 3 pounds per acre, and are fed off on the ground to sheep. The swedes are drilled 16 inches apart and hoed out to 9 inches in the rows; 2 pounds of seed are drilled per acre. Sewage is used for irrigating this crop to a moderate extent. Turnips and swedes usually follow either wheat, barley, or oats, although occasionally turnips are cultivated after rye grass.

Seeds, such as clover, trefoil, and alsike, are also grown to some extent. Clover is occasionally irrigated in dry seasons with moderate dressings of sewage. Generally, however, the seed crops are not irrigated.[1]

BIRMINGHAM PRECIPITATION WORKS AND FARM.

The sewage-purification works at Birmingham present some points of difference from those at the two English towns already considered. Thus Croydon and Leamington Springs are both residence towns purely, with a sewage consisting of ordinary house drainage without any manufacturing waste, whereas at Birmingham we have the sewage of a large residential area as well as that of one of the most extensive manufacturing districts in England.

The natural drainage of this district is into the River Tame, a small stream tributary to the Trent. At an early period the passage into these streams of large quantities of manufacturing refuse forced upon the Birmingham corporation the necessity of considering some form of sewage purification. In 1871 a special sewerage inquiry committee of the Birmingham common council reported at length as to the best means of treating the Birmingham sewage in order to prevent the serious pollution of the River Tame and its numerous small tributaries, which at that time threatened the corporation with damage suits on every hand. This report is specially referred to because of the thoroughness with which the inquiry was made by the committee. It is included in a volume of nearly 250 pages, and gives in succinct form a résumé of the whole question of sewage purification as it stood at that time. The committee recommended the exclusion of manufacturing wastes from the sewers and the purification of the sewage itself by intermittent filtration through the land. Subsequently the report of the committee was somewhat modified; the manufacturing wastes were allowed to go into the sewers, and a crude chemical precipitation treatment, to be followed by broad irrigation, was carried out.

[1] Further details of the Leamington farm may be found in the report of the Royal Agricultural Society's committee already referred to. Extended extracts have been made from this report because of the statement made by Mr. Castle that there has been no material change in the management of the farm at Leamington since that report was made in 1879.

Following on this line, the corporation applied to the Local Government Board, under the public health act of 1875, for an order to form a number of detached urban and rural sanitary districts into a united district for the purpose of sewage disposal. The total area of the drainage district, as now constituted, is 47,275 acres, with a stated population in 1894 of from 700,000 to 800,000.

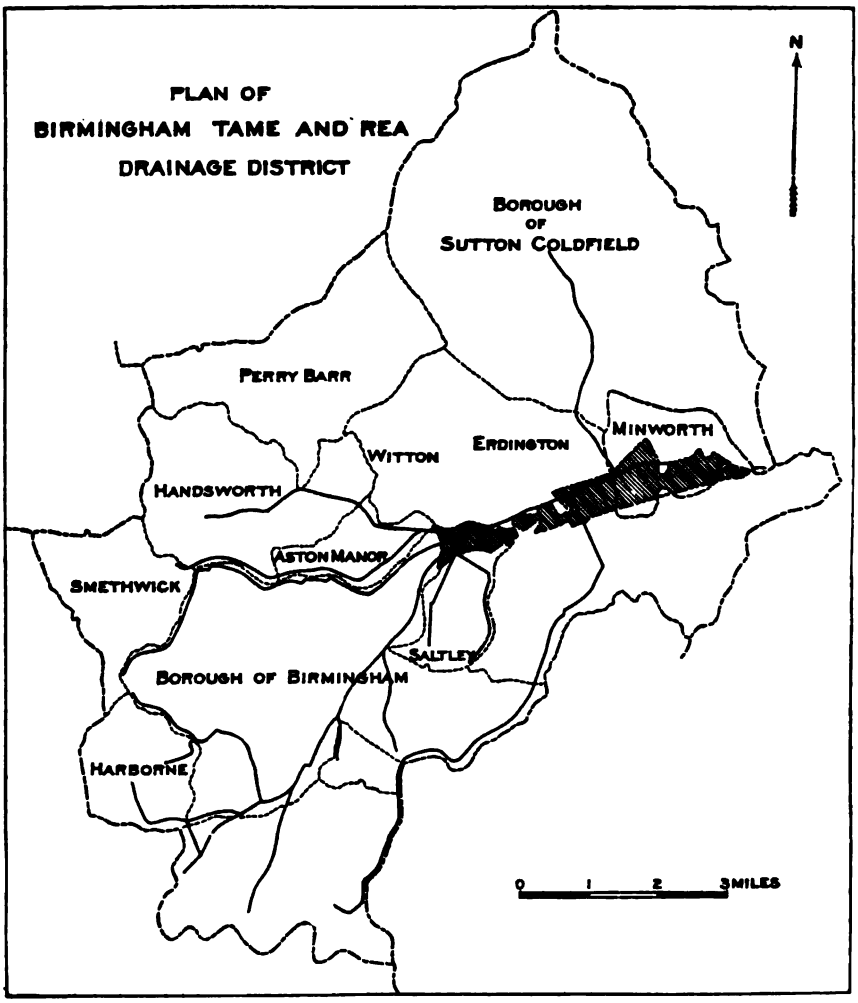


FIG. 20.—Plan of Birmingham Tame and Rea drainage district.

Beginning in 1880, the joint board of the Birmingham Tame and Rea Drainage District began the purchase of land for a sewage farm, and have gradually acquired, up to 1894, an area of 1,300 acres available for sewage disposal. Some of this land has been rented at the rate of £4 per annum per acre, while the cost of that of which the freehold has been purchased outright, including timber, buildings, mill

rights, tenants' compensation, etc., has amounted to £152 per acre. As stated by Mr. W. S. Till, city engineer of Birmingham, all this land is very favorable for the purification of sewage, the natural surface being, as a rule, even and unbroken and, with the exception of about 100 acres, of such a level as to admit of irrigating the entire area by gravitation. The subsoil is gravel and sand, varying from 6 to 10 feet in depth. The land is drained to a minimum depth of 4.5 feet, but in many cases, owing to the level nature of the area, a somewhat greater depth has been found necessary at the lower end of the drains. The drains consist of 3-inch and 4-inch agricultural drain pipes placed from about 45 to 65 feet apart and discharging into terra-cotta main drains of 9-inch, 12-inch, 15-inch, and 18-inch diameter, which in turn discharge into the main outfall channels. Roads 12 feet wide, with passing places at intervals, have been laid out in order to meet the various requirements of cultivation, as well as for the conveyance of produce. Farm buildings have been erected in a central position, with entrance lodge, manager's house, and a number of laborers' cottages. Several of the farm buildings and houses existing upon the area have been repaired and extended.

The method of treating the sewage as now carried on is described by Mr. Till substantially as follows: The sewage on arriving near the liming sheds at the upper end of the works is mixed with lime, both to neutralize the acids, which are present to an unusual extent in Birmingham sewage by reason of the large amount of iron manufacturing, and also to assist precipitation, which, however, is stated to be not necessary to so great an extent now as formerly.

The sewage then passes through large roughing tanks, where the coarser impurities are precipitated, whence it passes by the main conduit to the irrigation area, where it is further treated by ordinary irrigation on crops. In order to remove the sludge the precipitating tanks are cut out in regular order and the sludge is elevated by bucket dredges and pumps into movable wooden carriers, in which it flows into beds formed in the land in the vicinity of the precipitation plant. As it comes from the tanks the sludge contains about 90 per cent of water, but after lying on the ground for two weeks much of this water drains away or is evaporated, leaving the sludge in a layer about 10 inches thick and of a consistency which admits of its being dug into land. Crops are then planted on the sludge beds, and after a time the sludge becomes pulverized and capable of receiving irrigation. About 50 acres of land per year are required for sludge, and the same land may, if necessary, receive a coating of sludge once in two or three years. The amount of sewage now regularly treated is about 22,000,000 gallons per day. The controlling board farms the whole of the land itself, no portion being sublet.

The Birmingham sewage farm was visited by the author on October 26, 1894, and some facts were obtained in addition to those stated, which

are derived from a paper on the work of the Birmingham Tame and Rea District Drainage Board, by W. S. Till, C. E., engineer to the board, kindly furnished to the author by Mr. Till at the time of his visit. As one fact of interest, it may be mentioned that the men doing the work of digging the sludge into the land work in gangs and are paid by the cubic yard of sludge actually removed from the tank and dug into the land. Working in this way, they make from 28 to 30 shillings each per week. The cost of labor at Birmingham and vicinity has already been given on page 67.

According to a statement of the assistant farm manager, Mr. Henry Rumble, the land receiving sludge is now allowed to remain fallow until after the following winter, when it is plowed and put into rye grass, to be followed by cabbage, and finally, after about four years, celery is grown upon the land which has received sludge. The celery so grown is of fine quality; that seen growing and in process of gathering was the largest and finest celery the author has ever seen. The statement was also made that the celery from the Birmingham sewage farm brought a slightly higher price than that of the ordinary market gardens of the vicinity, by reason of its superior quality. In addition to rye grass, cabbage, and celery, crops of mangolds, swedes, kohlrabi, green-top turnips, potatoes, and roots of various kinds are raised. Large amounts of milk are sold, as well as beef cattle and swine. At the date of the author's visit a fine herd of 180 swine was observed on the farm.

The sewage farm itself is conducted on lines similar to those followed on farms previously visited, and little need be said in relation thereto. The precipitation tanks work on the continuous principle, and are arranged in the usual manner for cutting out in order to remove the sludge. At present about 1,120 pounds of lime are used per 1,000,000 gallons of sewage treated. Taking 22,000,000 gallons as the mean daily flow, we have then a total daily use of lime of about 24,600 pounds.

WIMBLEDON PURIFICATION WORKS AND FARM.

At Wimbledon we have still another interesting case of sewage purification, which differs in several particulars from those thus far described. This place is a residential suburb of London, situated only about 5 miles southwest of Westminster Abbey. The population is estimated at 26,000. The dry-weather flow of sewage amounts to about 780,000 gallons per day. The average wet-weather flow, which includes a considerable amount of storm water, is stated as about 50 per cent greater. The soil about Wimbledon consists of a heavy clay, on which it is impracticable to purify crude sewage by the ordinary methods of land treatment, especially in a dense residential district where only a limited area in a single body can be found. It became necessary, therefore, to treat the sewage by a crude process

of chemical precipitation or clarification before applying it to land in order to bring the whole treatment within the limits of the available area. The farm consists of 70 acres, of which 67 are irrigated.

The works have been designed with reference to first applying the treatment with lime or other chemicals, to be followed by broad irrigation. Detail as to the chemical part of the treatment may be obtained by reference to Mr. Crimp's Sewage Disposal, from which work, as well as the reports of the Wimbledon local board, the main statements of this paper, aside from those gathered by the author on a visit to the farm in question on October 22, 1894, have been taken.

An interesting feature of the works at Wimbledon is the disposal of the sludge, which is substantially as follows: From the settling tanks

FIG. 21.—Pile of pressed sludge at Wimbledon.

the sludge is swept, when necessary, into a sludge reservoir, whence it gravitates as desired into iron receivers. Lime is then thoroughly mixed with it and air pressure applied to the surface of the sludge, which is thus forced up through an iron pressure pipe into filter presses. The original filter presses employed were made by Johnson, but Mr. Crimp states that two of Goddard, Massey & Warner's now in use, of recent construction, possess improvements in detail over the original presses. As to the labor of sludge pressing, it is stated that the working expense at Wimbledon amounts to about 59 cents per ton of sludge pressed. It should be said that while two men are constantly employed at the work, they could easily press much more sludge if it were there to press. The cost of this item of work

may be expected, therefore, to decrease as the production of sludge increases.

The sludge is pressed into cakes and is stated to be readily sold at the works for about 1s. a ton. Ten tons of sludge as taken from the settling tanks is reduced to 2 tons of cake, 8 tons of water being pressed out. The total quantity of sludge produced in the year 1892 was 5,430 tons, while the total quantity in 1893 was 5,344 tons. It will be seen, therefore, that during those two years the flow of sewage must have been substantially the same. The 6 precipitating tanks in use have a total capacity of 530,000 gallons.

A statement of the annual receipts and expenditures in connection with the sewage farm from 1883 to 1893, inclusive, as derived from the annual reports of the Wimbledon local board, shows that, even with the difficult conditions for successful utilization prevailing at Wimbledon, the sewage farm has paid a small profit every year since it was started, except in 1892, which is said to have been a specially unfavorable year.

The crops grown are rye grass, mangolds, osier, and garden produce. The great decrease in the number of cows kept in and about London has reduced the amount obtained at present for rye grass to a much less figure than formerly. One of the most interesting points to be noted is the great number of good residences located near the farm. According to the statement of Mr. J. Snook, the farm manager, no complaints have been made by the adjacent residents for several years.

The effluent from the precipitation tanks is fairly clear, while the final effluent from the irrigation is bright and sparkling. As stated, the soil is of very heavy clay, which has been underdrained 6 feet deep with lines of drains 60 feet apart. The upper or surface soil has been lightened by mixing ashes with it. Ordinary plowing is to the depth of 1 foot, and once in about three years subsoil plowing to the depth of 2 feet is used. Root crops and cabbages are mostly grown in ridges, between which the irrigation is made.

As originally laid out there were a number of obvious errors in this farm which effectually prevented for several years either a thorough purification of the sewage or a satisfactory utilization of it in agriculture on the heavy clay soil. At the present time the ashes of the town are regularly taken out upon the farm and mixed with the top soil for the purpose of lightening it. Filters of burnt clay have also been constructed for the purpose of receiving storm waters during periods of heavy rainfall. The settling tanks are also provided with valves, by means of which any excess of sewage, due to sudden storms, escapes and is discharged upon these filter beds. These storm-water filters are used on an average from eight to twelve times a year.

The main carriers of this farm are composed of cast-iron pipes, from which the sewage is drawn as desired at different points by means of ordinary sluice valves. The secondary carriers leading from the cast-

iron mains are either concrete or stoneware half pipes, laid as shown in fig. 5. The distributaries are laid with a plow and finally finished by spade labor. As a general rule their direction is that of the greatest fall. The distributing channels are cut at a definite distance of 33 feet apart, in order that when cutting the grass the laborer may know the area of the piece he is cutting, as the rye grass when sold standing is disposed of by the square yard.

There is less variety to the crops on this farm than on the others described, because of the large quantity of sewage disposed of per area. Italian rye grass, mangolds, and osiers, the three main crops grown, are those which best stand large quantities of sewage without difficulty.

Experience on the heavy clay lands of this farm indicates that ground to be sown with rye grass should be plowed deeply in the autumn and allowed to remain in the furrow during the winter, in order that the soil may be broken down by the disintegrating action of frost. There is no objection to frequent applications of sewage during this period. As early as practicable in the spring the land should be pulverized by harrowing and the rye grass sown to the amount of not less than from 4 to 5 bushels of selected seed per acre. At Wimbledon the grass grows very rapidly, and with favorable weather the first cutting is sometimes made within eight weeks after sowing. The cuttings immediately succeeding will be heavier than the first, the plant deteriorating rapidly after five or six cuts have been removed. For the best results in the production of forage, rye grass should not be allowed to flower, as a loss of over 50 per cent in weight follows the flowering stage. With favorable conditions and sufficient applications of sewage, as many as eleven cuttings, weighing in the aggregate in the green state about 100 tons, have been obtained in the two seasons following the planting of the seed. After two seasons deep plowing and subsoiling should, if necessary, be resorted to, and the process gone through again. With good cultivation, rye grass may be grown for several years on such heavy soils as those at Wimbledon. The average price obtained for the rye grass at Wimbledon was stated by Mr. Snook to be about £15 to £20 per acre per annum. In some years more than this may be obtained.

In regard to osiers, it was stated that this has been found one of the most valuable crops raised. The demand has always thus far been good, since large quantities are annually imported for basket making and other purposes from Holland and the north of France. This plant likes moisture, and, so far as known, will grow upon any kind of land except peat bog. The kinds found most suitable at Wimbledon are the new osier and the golden willow. The first named is dark skinned and very suitable for basket making. The golden willow is smaller and of finer growth than the osier.

In setting an osier field, sets or cuttings are selected from growing

willows, which are cut in lengths of about 16 inches and planted about 1 foot apart in one direction and about 1½ feet in the other. The cuttings should be planted with their ends nearly level with the ground in order to insure straight shoots. They come into full bearing in the third year, although a fair crop may be got the first year. The maximum growth is attained in about ten years, after which the plant slowly declines, and in the course of fifteen to twenty years it will require reseeding.

The crop is gathered soon after the fall of the leaves by cutting as close to the main stock as possible. The annual yield per acre is stated at from 6 to 7 tons. The price obtained at Wimbledon is about £12 per acre per annum for the rods. This is for osiers; the golden willow yields less and does not bring so high a price as the osier.

The effluent from the Wimbledon farm flows into the River Wandle. As observed by the author, just above the point of junction with the river it was in every way as bright and sparkling as any stream flowing from agricultural lands.

DONCASTER FARM.

As another interesting example of sewage purification and utilization by broad irrigation, we may briefly refer to the farm at Doncaster, which, however, was not visited by the author, but of which it is deemed well to give an account, because Doncaster, while not receiving a prize in the Royal Agricultural Society's sewage farm competition of 1879, was still strongly commended by the committee in their report as an admirable example of thrifty management and an excellent illustration of how sewage can be applied in general farming.

The population of Doncaster is stated at about 30,000 at the present time, with a dry-weather flow of sewage of 700,000 gallons per day. The main drainage works of the town were carried out in 1870, but soon thereafter an injunction was obtained against the Doncaster corporation restraining them from discharging sewage into the River Don. In consequence of this injunction sewage-disposal works were established in 1873. The area available for sewage disposal is about 278 acres, with a very undulating surface. The soil varies between the limits of light sand and stiff red stratified clay. There is also an area of about 20 acres of pasture land laid out for sewage irrigation.

The principle of surface preparation followed was, by reason of the undulations, to change the surface as little as possible. According to Mr. Brundell, the designing engineer, no attempt was made to alter the surface, but the flow of sewage was fitted to the surface by the use of main carriers led along the summits and from them by means of contour distributaries the sewage was finally led over the entire area. Figs. 7 to 13 show how the distribution of sewage on such an area may be treated.

The main carriers are of terra-cotta pipe, laid either below the sur-

face or in embankments, as may be required. This form of carrier has already been referred to, and is illustrated by fig. 5. The pipes are sometimes worked under a small head. The sewage is pumped from the borough of Doncaster out onto the sewage farm, a 21-inch cast-iron main with a total rise of 22 feet being used for this purpose.

A great variety of crops are produced on this farm. According to the report of the judges in the Royal Agricultural Society's sewage farm competition, they have been successful in raising black currants, gooseberries, wheat, barley, oats, rye, beans, potatoes, turnips and swedes, clover, clover seed, rye grass, meadow grass, and osiers. A considerable amount of live stock is also kept upon the farm. In the early days there was some prejudice against the milk produced, but it is now accepted without hesitation. The effluent is stated to flow into the River Don in a state of much greater purity than the water of the river itself, which is seriously polluted by the towns above Doncaster.

SEWAGE UTILIZATION IN GERMANY.

The sewage farms of Berlin are the most extensive thus far carried out. Since they exemplify both in their preparation and management the best scientific sewage farming of the present day, attention will be confined to a consideration of them, although descriptions might well be given of the large farms at Dantzic, Breslau, and other points.

BERLIN SEWAGE FARMS.

The information concerning these farms was obtained by inspection by the writer in November, 1894, and from a paper on the sewage farms of Berlin by Mr. Roechling, to be found in Volume CIX of the Proceedings of the Institution of Civil Engineers. The detailed statistical statements, as published annually by the Berlin authorities, for the years from April, 1891, to March, 1893, are also at hand. Inasmuch as Mr. Roechling's paper covers nearly every phase of sewage farming at Berlin, it has been used in some sort as a syllabus in preparing this short account.

At the date of the last census, in December, 1890, the population of Berlin was 1,578,794, the area on which this population is located amounting to about 24½ square miles. The area, not only of the city of Berlin, but of the surrounding country, is generally level. The only stream of any size is the River Spree, flowing through the middle of the city, which, however, is far too small to admit of the discharge of the sewage of a city of the size of Berlin without treatment.

The sewerage system, as designed by Mr. Hobrecht, the city engineer, is what is known as the radial system, wherein the entire area has been divided into twelve separate districts, which, so far as the collection of the sewage is concerned, are independent of one another. Each district has a pumping station, from which the sewage is raised

direct to the sewage farms, although in some cases two drainage districts are united to one main. This peculiarity of the Berlin system has determined largely the location of the farms at several different points about the city.

The River Spree flows from west to east through the city. From the systems north of the river the sewage is sent northward, and from the south of the Spree, south; so that, with the exception of a single 12-inch pipe, no sewer or pumping main has been carried under the river. The southern farms are located at a distance from the central part of the city of as much as 12 miles. This makes the disposal of farm produce somewhat difficult. The north and northeast farms are only about one-half the distance of the southern farms from the center of the city, and, consequently, it is stated that the produce there-

FIG. 22.—General view of the North Berlin sewage farms, the village of Malchow in the distance.

from is far more readily disposed of than that of the farms to the south. This statement is made by the Berlin authorities as a reason why the northern farms show better financial returns than the southern.

The general character of the area included in the Berlin sewage farms is well shown by fig. 22, from a photograph. The most of it is practically level, although there are frequently small eminences attaining a height of from 10 to 15 feet above the general level. The soil is generally light and sandy, although in the northern farms there are considerable patches of clay. The subsoil is coarse, open material for nearly the whole area. Taken as a whole, the soil is well adapted for sewage irrigation.

The total area of the Berlin sewage farms as they existed in 1894 is stated at about 20,000 acres, although only a little over half of this was under irrigation at that time. This great property is not only all owned by the municipality, but is mostly farmed by it as well. During the last few years, however, there has been considerable demand for land by market gardeners, who rent the land and take sewage only when they desire it, whence it has resulted that the area farmed by the city itself has been somewhat lessened. The leased land is first prepared for irrigation by the city and then rented out as required. The annual rental for this prepared land is about $21 per acre, while ordinary land in the vicinity brings only about $8.50 per acre, the difference of $12.50 per acre being due to the increased value of land with sewage irrigation. There has also been a demand for rental of

FIG. 23.—An effluent channel on the Berlin sewage farm.

sewage by the farmers who prepare their own land and only take the sewage as required for the best results. In 1894 sewage was applied to about 1,000 acres in this way.

In considering the results of sewage irrigation at Berlin it should be remembered that the water supply has by metering been kept at a very low point, so that the daily use of sewage amounts to only about 14 or 15 gallons per capita. Including the storm water, the daily flow of sewage averages about 25 gallons per capita. The sewage is therefore more concentrated than that of any town thus far considered.

The rising mains from the pumping stations terminate at standpipes erected on the highest points at various parts of the farms. These are open at the top and act as safety valves as well as pressure gauges

for indicating the actual head on the mains at any particular instant, this fact being indicated by a float on the inside of the pipe carrying a flag by day and a lantern by night. On account of the location of the standpipes on the highest points, they form landmarks visible from all parts of the farms. The distributing pipes of cast iron start from the standpipes and radiate in all directions to various parts of the farms, their diameters being reduced gradually at their farther extremities. At various places they are provided with sluice valves and side branches which empty into small tanks dug into the ground. The open earth carriers begin at these tanks. There are sluice gates on the distributing pipes at intermediate points as required.

The laying out of the Berlin farms has been done according to the following scheme: The open effluent ditches, of which an example is shown in fig. 23, follow along the lowest levels of the farm; the bottom width is about 18 inches and the side slope 1½ to 1. The farm has been thoroughly underdrained, mostly with 2-inch pipes laid on the parallel system at distances varying from 16 to 33 feet. The average depth of the feeders is from 3 to 4 feet. The feeders lead into master drains varying in size from 3 to 6 inches, which finally lead into the main effluent ditches just referred to.

In designing the beds the topographical conditions of the ground were very carefully taken into account, and generally sloping ground was utilized for grass plats, to be treated by broad irrigation. The nearly level portions have been made into filtration areas, and the level ground into tanks in which surplus sewage can be filtered by intermittent filtration as required. The irrigation and filtration plats are, so far as possible, rectangular in form, with areas of from 5 to 6 acres. The tanks, however, are larger. They include plats of ground from 5 to 22 acres in extent, surrounded by embankments about 3 feet in height and from 13 to 20 feet wide at the top, in order to furnish space for wagon roads. In summer the tanks are used as filters to dispose of storm waters, and in winter they are used as reservoirs at such times as, owing to long-continued frost, the land is frozen to a depth preventing ordinary irrigation. The Berlin authorities consider the tanks as a necessary adjunct of any sewage farm operated like that at Berlin, although the degree of purification effected by them is apparently not so high as that of the grass plats or the filtration beds. The 5 or 6 acre plats are also subdivided into what are called quarters, in order to enable the irrigation to be properly applied.

Reference has already been made to the earth tanks at the outlets of the main distributaries. The main carriers, which are merely ditches cut in the ground, illustrated by fig. 4, start from these. They vary in depth from 18 inches to 3 feet, and, entering each 5 or 6 acre plat at the highest corner, pass down one side to the lowest quarter to be irrigated, and so on to the next plat. Secondary car-

riers, which are also mere earth trenches, are taken off from the main carriers to irrigate such plats as the main carriers do not traverse. From the secondary carriers the sewage is distributed over each plat and quarter thereof by still smaller earth carriers, which are frequently furrows cut with the plow.

The surface of the permanent grass plats has been graded to a uniform slope and the irrigation takes place from the level furrow at the upper end, which, when full, overflows, allowing the sewage to pass in a thin film down the slope. This method of irrigating the grass plats is the one generally followed at Berlin.

The beds have been laid out in terraces, each terrace being made level and separated from the one below by an embankment. The cultivation beds are formed with ridges about 3 feet wide, with the furrows between the ridges 2½ feet wide and 1½ feet deep. Sewage flows into the ditches from one side until nearly full, when it is allowed to stand and filter away through the soil. Turnips, mangolds, cabbages, and other root and vegetable crops are grown on the filter beds.

The foregoing account of the method of laying out pursued at Berlin indicates that both broad irrigation and filtration are used on the Berlin sewage farms, the grass plats representing the broad irrigation and the level beds intermittent filtration with cultivation, while the tanks represent intermittent filtration without any attempt at utilization. As we have seen, this principle is the one now universally adopted in the laying out and management of modern sewage farms. We may conclude, also, from what has preceded, that the principle of leasing sewage to private farmers is developing with considerable rapidity at Berlin, which is in line with the best results in agricultural utilization.

As indicated on page 58, the crops raised at Berlin include a considerable variety of roots, cereals, and ordinary vegetables, as well as oil seeds, which are grown quite extensively. Detailed statements of the yields may be found in either Mr. Roechling's paper in the Proceedings of the Institution of Civil Engineers, already referred to, or in the annual statements published by the city of Berlin of more recent date. These statements show a loss during the early years of these sewage farms, but since the laying out of the farms was completed and more experience has been gained they have shown some small profit.

While the rainfall at Berlin is not large for the whole year, it is heaviest during the growing months, which complicates somewhat the problem of sewage irrigation there.

The best returns have come from the Falkenberg farm, which in 1890 earned about 3¼ per cent on the capital expenditure. This must be considered a very favorable result, especially when it is understood that ordinary land in the vicinity of Berlin does not give an average yield of more than 3 per cent. In comparing the results of

sewage farming at Berlin with ordinary farms it should, however, be borne in mind that the foregoing figures do not include any rent for the land. In case a rental of as much as $5 per acre (20 marks) were to be included, the farms would hardly be more than self-supporting. It is the opinion of the managers of the Berlin farms that with the gradual improvement in the condition of the area under cultivation for a number of years the profits of sewage farming may be expected to increase somewhat. As remarked by Mr. Roechling, the degree of purification attained is the chief test to be applied to a sewage farm; and if wanting in this respect, the farm must be said to be a failure. This point is specially important to bear in mind in considering questions of sewage purification and utilization, because, with the evidence at hand, it is indisputable that with proper management sewage farms may be so operated as to not only utilize sewage at an agricultural gain, but also to give out an effluent of a very high degree of purity. At Berlin the water flowing in the effluent ditches is as clear and sparkling as any flowing from agricultural lands, and the author was informed by one of the head gardeners in the course of walking over the farms that the laboring men who carry their dinners out in the fields were in the habit of frequently taking water from the effluent ditches for drinking, and this, too, in spite of the fact that the use of the water for this purpose had been prohibited by the authorities in charge.

A large number of analyses have been made not only of the Berlin sewage as it comes to the farms, but also of the final effluent. The results are given in such detail as to render any adequate presentation impossible at this place for lack of space. They may be found in Mr. Roechling's paper or in the annual municipal statements. In a general way they indicate that the purification attained is in the highest degree successful.

SEWAGE UTILIZATION IN FRANCE.

Sewage utilization in France, as a whole, has been less generally attempted than in either England or Germany, although the employment of Paris sewage on the Plain of Gennevilliers is, perhaps, on the whole, the most successful case of profitable utilization in agriculture to be found anywhere. The soil of that plain is exceedingly well adapted for the purpose, being light and open, with gravel subsoil of considerable depth. It therefore serves the purpose of a natural filter. Thus far only a small portion of the sewage of the city of Paris has been utilized at Gennevilliers, the remainder being allowed to pass directly into the River Seine. Only a portion of the sewage of Paris is water carried, the balance being disposed of by the pail system, although a recent decree of the French Senate makes it imperative to now construct sewers and connect all houses with the water-carriage system.

The utilization of all the sewage of Paris by irrigation has been discussed extensively by the engineers of the city and by Government commissions for many years, with the final result that under a decree of the Senate, bearing date July 10, 1894, the municipality of Paris is authorized to make a loan of 117,500,000 francs for the purpose of extending the sewers to those districts of the city which are now served by the pail system, and also for preparing the necessary areas for land purification at various points in the vicinity of the city.

THE PLAIN OF GENNEVILLIERS.

The history of the irrigation at Gennevilliers is exceedingly interesting. As the result of a considerable discussion, the municipality in 1869 laid down at its own expense the necessary carriers, subcarriers, conduits, and pipes for distributing sewage on land at this place and conceded to the owners and lessees the free use of it until 1880, since which time they have been obliged to pay a price for the use of the sewage. At first there was very great prejudice against not only the use of the sewage as manure, but also against the produce grown by its aid. This gradually died out, and the number of users of sewage has increased from year to year, until in 1891 the total area available at Gennevilliers, which amounts to about 776 hectares, or 1,917 acres, was taken up.

The crops grown under sewage irrigation at Gennevilliers have been successful in the highest degree. They comprise absinth, artichokes, asparagus, beans, beets, cabbages, carrots, celery, kohl-rabi, cucumbers, leeks, melons, onions, parsnips, peppermint, potatoes, pumpkins, spinach, tomatoes, turnips, clover, rye grass, mangolds, wheat, oats, and Indian corn. The market-garden produce yields abundant crops. Indian corn has also an exceedingly good growth here, the stalks attaining a height of from 9 to 10 feet. In order to obtain definite information as to the results to be derived in the agricultural utilization of sewage on the Plain of Gennevilliers, the French minister of agriculture in 1874 appointed a commission to study the question in its economical aspects. The report of this commission shows the following as the yields of vegetables which under favorable conditions may be expected there: Cabbage, as much as 75,000 kilograms to the hectare.[1] Mangolds are stated as yielding 120,000 kilograms per hectare; carrots, 50,000 kilograms per hectare, and beans 15,000 kilograms per hectare. The experience of the last few years is stated to fully confirm the results of the commission of 1874.

Artichokes, which are extensively grown for consumption in France, are stated to yield from 36,000 to 50,000, and even as many as 80,000, heads per hectare. Cauliflowers amount to from 35,000 to 40,000 kilograms per hectare. Garlic yields 37,000 kilograms per

[1] The kilogram is equivalent to 2.2 pounds, and the hectare to 2.47 acres; hence the stated yield of cabbage, in our measures, is 34.14 tons per acre.

hectare; celery, 100,000 kilograms per hectare; onions, 60,000 to 80,000 kilograms per hectare; potatoes, 30,000 to 40,000 kilograms; salsify, 10,000 to 12,000 heads, or 25,000 kilograms, to the hectare.

As to the mean value of the number of crops raised, the following figures are given: Cabbage, from 3,000 to 4,000 francs per hectare; cauliflowers, 5,000 to 10,000 francs per hectare; carrots, 3,000 francs; artichokes, 5,000 to 6,000 francs; onions, 3,500 francs per hectare, etc. (three thousand five hundred francs per hectare amounts to 1,416 francs, or about $281, per acre.) The French reports abound with statements as to the degree of purification attained at Gennevilliers, but these are omitted in this place for lack of space. The author visited the Plain of Gennevilliers on a rather warm day early in December, 1894. The effluent was bright and sparkling, and as he was

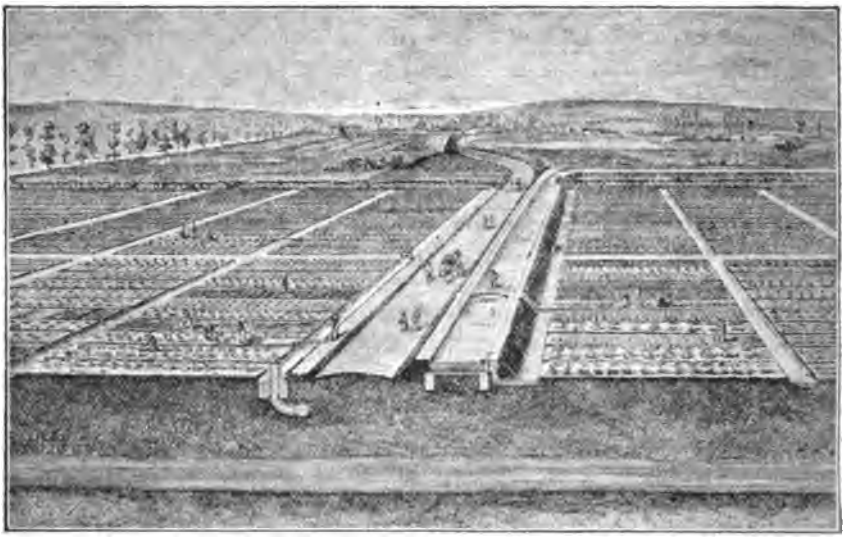


FIG. 24.—Diagrammatic view of the irrigation fields at Gennevilliers.

exceedingly thirsty after a long walk he had no hesitation in dipping up the water of the effluent channel and drinking it, the gentleman accompanying him having made the positive assurance that no harm would result therefrom. Thus far there is no reason to believe that the effluent from sewage irrigation from the Plain of Gennevilliers may not be used as drinking water regularly with impunity.

The available area at Gennevilliers having been all taken up, the engineers of the city of Paris proposed to extend a main for irrigation to the edge of the forest of St. Germain, a few miles distant from the municipal usine at Clichy, the point from which the sewage is diverted from the main outlet sewer of Paris to the Plain of Gennevilliers. Although the sewage irrigation at Gennevilliers had been very successful, the project of irrigation in the forest was opposed strongly by the citizens of the neighboring communes. Petitions were made and

protests forwarded to the French Senate, the whole forming a large volume of considerable interest as indicating the persistency of the public opposition to the carrying out of great works of public utility of this character. On the part of the city of Paris, however, an equal persistency has been manifested, with the result that the city has finally received authorization to carry out the scheme of purification of Paris sewage, as already detailed in discussing the decree of July 10, 1894.

Among other interesting statistics which have been gathered in regard to sewage purification at Gennevilliers, the French reports indicate that, as in England and at Berlin, the health of people living on and about the sewage farms has not been in any degree impaired. So extensively has the evidence on this point multiplied from the different places where sewage utilization works have been carried out that we may conclude here, as in respect to other details already discussed,

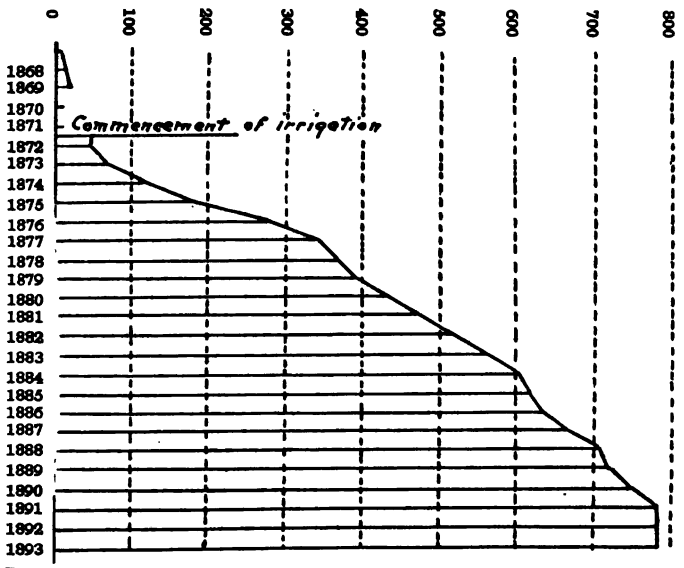


FIG. 25.—Diagram illustrating increase in use of sewage at Gennevilliers. The numbers denote hectares.

that properly conducted sewage utilization is not in any degree prejudicial to the health of either the people engaged in it or those living in the vicinity.

Among other interesting features at Paris, the Model Garden should be mentioned. This includes an area of 6 hectares, on which precise experiments as to the utilization of sewage have been carried on for a number of years under the most scientific conditions possible of attainment, in which have been noted the weight of seed sown, the yield therefrom, the amount of sewage applied, the amount of rainfall, variation in quantity of sewage applied, and many other things tending to afford a definite scientific basis of positive information for the agricultural utilization of sewage.

The results of the experiments at the Model Garden have never been published in full, and the author is indebted to Mr. George Bechmann, chief engineer of the sanitary department of the Seine, for information as to these valuable results. As visited in December, 1894, the Model Garden presented evidence of the many careful and systematic experiments carried out, although at that season of the year little idea could be formed of the relative benefits of sewage to different crops, for the reason that crops were not then growing.

The following particulars as to the irrigation of Gennevilliers are derived from the report of Mr. Bechmann for the year 1893. According to the report, the area under irrigation has remained stationary at 776 hectares since 1891, in which year, as already stated, the entire available area was taken up. Of this area of 776 hectares, 6 hectares belong to the city of Paris and constitute the Model Garden and its dependencies. The remainder is composed of various-sized parcels which are the property of the individual cultivators, who receive sewage only when they desire it. Fig. 25 shows graphically the increase in the use of sewage in Gennevilliers from year to year.

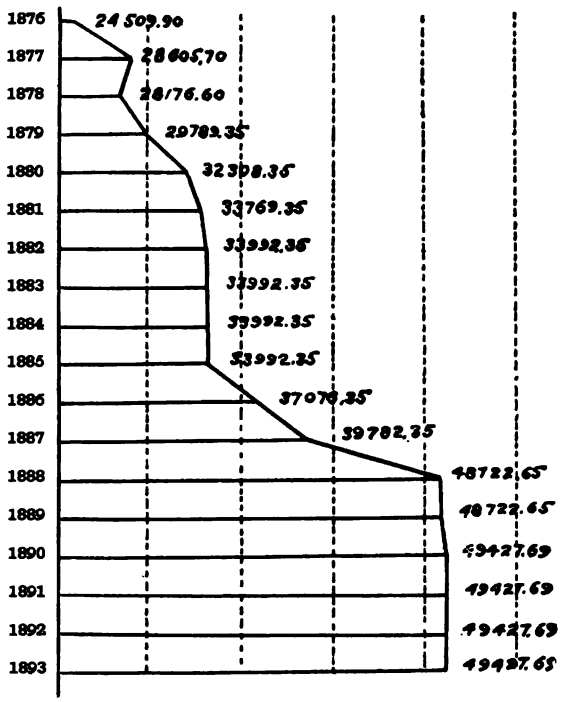


FIG. 26.—Diagram illustrating progressive increase in length of distribution conduits at Gennevilliers. The numbers denote meters.

The sewage is distributed by means of a system of main and secondary channels, with a total length at the present time of 49,427.7 meters. The progressive increase in length of these conduits from the beginning to 1893 is shown by fig. 26. The distribution service is in charge of the agents of the city of Paris, who work according to a system, irrigating successfully the three belts into which the plain has been divided. The force having this work in charge consists of 3 foremen and 23 ordinary workmen, who perform all the labor necessary for a proper and successful distribution of the sewage. Foremen receive 170 francs per month and laborers from 145 to 150 francs per month.

The total volume of sewage distributed in 1893 was 33,421,299 cubic meters. Each hectare of the plain, therefore, received on an average a little more than 43,000 cubic meters, the distribution per acre being, thus, 625,293 feet. The amount actually distributed each month is shown by fig. 27, while the least area irrigated in one day varied from month to month as per fig. 28. From this figure we learn that the minimum area per day was 49 hectares in February, and the maximum area 133 hectares per day in September.

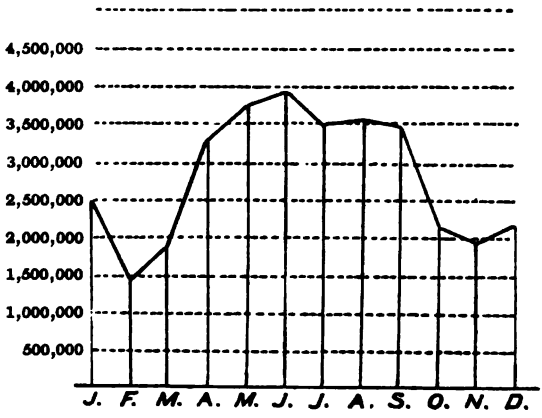


FIG. 27.—Diagram illustrating distribution of sewage by months at Gennevilliers. The numbers denote cubic meters.

Of the 6 hectares belonging to the city of Paris and included in the Model Garden, 3 hectares and 85 ares were rented in 1893 at an annual rental of 600 francs per hectare. The remainder of the 6 hectares was devoted to various experiments, principally to intensive irrigation, wherein from 80,000 to 130,000 cubic meters of sewage per hectare per year were applied. Mr. Bechmann states that the application of such large quantities of sewage is not prejudicial either to the purification or to the success of the crops. The experiments at the Model Garden have been directed specially for a few years toward the cultivation of nursery stocks of various sorts, and the results obtained are stated to have been remarkably good.

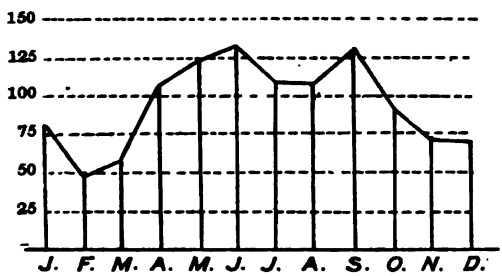


FIG. 28.—Minimum amount of sewage distributed per day by months in 1893. The numbers denote hectares.

The cost of the irrigation at Gennevilliers is said to have been 0.0022 franc per cubic meter of sewage distributed. In our currency this would amount to 0.00043 cent per cubic meter.[1]

The purification attained during the year 1893, as determined by a series of analyses regularly made at the municipal observatory of Montsouris, continues to be absolutely satisfactory. Without referring to the degree of purification attained as indicated by chemical

[1] The cubic meter equals 35.94 cubic feet, or 1.33 cubic yards.

analyses, we may merely call attention to the bacterial purification. According to the Montsouris laboratory determination, the sewage as it flows in the Clichy main contains 29,454,000 bacteria per cubic centimeter, while the water of the Asnieres effluent drain contains only 5,380 bacteria per cubic centimeter, and that of the Epinay drain 26,500 bacteria per cubic centimeter.

The foregoing is an exceedingly inadequate account of sewage utilization at Paris. The literature of the subject has grown very extensive, and whoever would familiarize himself with all that has been done at Paris must go through this large mass of literature in detail.

SEWAGE PURIFICATION IN THE UNITED STATES.

At the present time there are upward of 60 sewage-disposal plants in operation in the United States and the Dominion of Canada. The limited space here available will not permit an account of these works, but in a subsequent pamphlet of this series it is intended to give a brief description of a few of the more recent or more interesting establishments. Facts concerning many of these may be found in the columns of Engineering News and Engineering Record and in Sewage Disposal in the United States, which latter contains descriptions of and reference to works built in the United States previous to 1893. A complete discussion of existing American works would fill a large volume.

As examples of sewage utilization we may refer to Pullman, Illinois; Los Angeles, California; South Framingham, Massachusetts; Meriden and Bristol, Connecticut; and Plainfield, New Jersey. Intermittent filtration without any attempt at sewage utilization is also practiced at Marlboro, Brockton, and North Brookfield, Massachusetts; Summit, New Jersey; Pawtucket, Rhode Island; and also at a number of other towns. Examples of precipitation plants may be seen at Worcester, Massachusetts, and Canton, Ohio.

Much has been done toward advancing knowledge of sewage purification in this country. At the present time the scientific part of the subject is somewhat in advance of the practical application, and herein lies ground for criticism. The managers of American works have frequently failed to understand the importance of closely following rational theory. It is believed that with good management the American works can be quickly made to show as good results as can be obtained anywhere, for generally they have been well designed—a fact which may be set down to the credit of the engineers.

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1894.

Report on agriculture by irrigation in the western part of the United States at the eleventh census, 1890, by F. H. Newell, 1894, quarto, 283 pp.

Consists of a general description of the condition of irrigation in the United States, the area irrigated, cost of works, their value and profits; also describes the water supply, the value of water, of artesian wells, reservoirs, and other details; then takes up each State and Territory in order, giving a general description of the condition of agriculture by irrigation, and discusses the physical condition and local peculiarities in each county.

Fourteenth Annual Report of the United States Geological Survey, 1892-93, in two parts, Part II, Accompanying papers, 1894, octavo, 597 pp.

Contains papers on potable waters of the eastern United States, by W J McGee; natural mineral waters of the United States, by A. C. Peale; results of stream measurements, by F. H. Newell. Illustrated by maps and diagrams.

1895.

Sixteenth Annual Report of the United States Geological Survey, 1894-95, Part II, Papers of an economic character, 1895, octavo, 598 pp.

Contains a paper on the public lands and their water supply, by F. H. Newell, illustrated by a large map showing the relative extent and location of the vacant public lands; also a report on the water resources of a portion of the Great Plains, by Robert Hay.

A geological reconnoissance of northwestern Wyoming, by George H. Eldridge, 1894, octavo, 72 pp. Bulletin No. 119 of the United States Geological Survey; price, 10 cents.

Contains a description of the geologic structure of portions of the Big Horn Range and Big Horn Basin, especially with reference to the coal fields, and remarks upon the water supply and agricultural possibilities.

Report of progress of the division of hydrography for the calendar year 1893-94, by F. H. Newell, 1895, octavo, 176 pp. Bulletin No. 121 of the United States Geological Survey; price, 15 cents.

Contains results of stream measurements at various points, mainly within the arid region and records of wells in a number of counties in western Nebraska, western Kansas, and eastern Colorado.

1896.

Seventeenth Annual Report of the United States Geological Survey, 1895-96, Part II, Economic geology and hydrography, 1896, octavo, 864 pp.

Contains papers by G. K. Gilbert on the underground water of the Arkansas Valley in eastern Colorado; by Frank Leverett on the water resources of Illinois; and by N. H. Darton on a reconnaissance of the artesian areas of a portion of the Dakotas.

Artesian-well prospects in the Atlantic Coastal Plain region, by N. H. Darton, 1896, octavo, 230 pp., 19 plates. Bulletin No. 138 of the United States Geological Survey; price, 20 cents.

Gives a description of the geologic conditions of the coastal region from Long Island, N. Y., to Georgia, and contains data relating to many of the deep wells.

Report of progress of the division of hydrography for the calendar year 1895, by F. H. Newell, hydrographer in charge, 1896, octavo, 356 pp. Bulletin No. 140 of the United States Geological Survey; price, 25 cents.

Contains a description of the instruments and methods employed in measuring streams and the results of hydrographic investigations in various parts of the United States.

Survey bulletins can be obtained only by prepayment of cost as noted above. Postage stamps, checks, and drafts can not be accepted. Money should be transmitted by postal money order or express order, made payable to the Director of the United States Geological Survey. Correspondence relating to the publications of the Survey should be addressed to **The Director, United States Geological Survey, Washington, D. C.**

WATER-SUPPLY AND IRRIGATION PAPERS.

1. Pumping water for irrigation, by Herbert M. Wilson, 1896.
2. Irrigation near Phœnix, Arizona, by Arthur P. Davis, 1897.
3. Sewage irrigation, by George W. Rafter, 1897.
4. A reconnoissance in southeastern Washington, by Israel C. Russell, 1897.
5. Irrigation practice on the Great Plains, by E. B. Cowgill, 1897.
6. Underground waters of southwestern Kansas, by Erasmus Haworth, 1897.
7. Seepage waters of northern Utah, by Samuel Fortier.
8. Windmills for irrigation, by E. C. Murphy.
9. Irrigation near Greeley, Colorado, by David Boyd.
10. Irrigation in Mesilla Valley, New Mexico, by F. C. Barker.

In addition to the above, there are in various stages of preparation about twenty other papers relating to the measurement of streams, the storage of water, the amount available from underground sources, the efficiency of windmills, the cost of pumping, and other details relating to the methods of utilizing the water resources of the country. Provision has been made for printing these by the following clause in the sundry civil act making appropriations for the year 1896-97:

Provided, That hereafter the reports of the Geological Survey in relation to the gauging of streams and to the methods of utilizing the water resources may be printed in octavo form, not to exceed 100 pages in length and 5,000 copies in number; 1,000 copies of which shall be for the official use of the Geological Survey, 1,500 copies shall be delivered to the Senate, and 2,500 copies shall be delivered to the House of Representatives, for distribution. (Approved, June 11, 1896; Stat. L., vol. 29, p. 453.)

Application for these papers should be made either to members of Congress or to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
Washington, D. C.

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54TH CONGRESS, 2d Session. } HOUSE OF REPRESENTATIVES. { DOCUMENT No. 344.

DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 4

A RECONNOISSANCE IN SOUTHEASTERN WASHINGTON.—RUSSELL

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1897

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

A RECONNOISSANCE IN SOUTHEASTERN WASHINGTON

BY

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A RECONNOISSANCE IN SOUTHEASTERN WASHINGTON.

By Israel C. Russell

INTRODUCTION.

Acting under the instructions of Mr. F. H. Newell, hydrographer of the United States Geological Survey, I made an examination of the geology of the southeastern portion of the State of Washington in the summer of 1896 for the purpose of ascertaining how far the nature and position of the rocks of that region favor the hope of obtaining artesian water. The time devoted to field work extended from August 11 to September 21. The region traversed embraces about 5,000 square miles. It will be seen at once, from the time available and the extent of territory examined, that nothing more than a general, or, perhaps more accurately, a preliminary, reconnoissance was aimed at. The conditions, however, are unusually favorable for rapid geological exploration, the region being practically free from forests and the rocks nearly horizontal. For these reasons more confidence, I think, can be placed in the results obtained than at first thought might seem warrantable.

The region examined.—The country chosen for the commencement of my studies is that portion of southeastern Washington which lies south of Snake River. By referring to the accompanying map, it will be seen that a well-defined region, bordered on the south by Oregon, on the east by Idaho, on the north by Snake River, and on the west by the Columbia, may be briefly designated as lying south of Snake River. It is frequently spoken of as the "Walla Walla country," for the reason that Walla Walla is the principal town, or perhaps because the whole of it was formerly included in Wallawalla County.[1] At present this region is divided into four counties, namely, in their order from west to east, Wallawalla, Columbia, Garfield, and Asotin.

[1] Wallawalla County was established in 1854, and originally embraced a much wider territory than is mentioned above, as it extended from the Cascade Mountains eastward to beyond the present eastern boundary of Washington.

The region bounded as described above embraces about 4,000 square miles. In order to learn its geological history, however, it was found desirable to make an excursion southward into Oregon as far as Wallowa, about 30 miles in a straight line south of the Washington-Oregon boundary, and another northward, traveling by rail, through the eastern border of the "Palouse country," as far as Spokane. The hasty reconnoissance northward included a visit to Pullman, Palouse, Garfield, and Spokane. Short excursions were made from each of these towns, and the more general features in the geology of their environs were ascertained. The excursions mentioned were of much assistance in understanding the geology of the region south of Snake River, which is the portion of Washington definitely considered in this report.

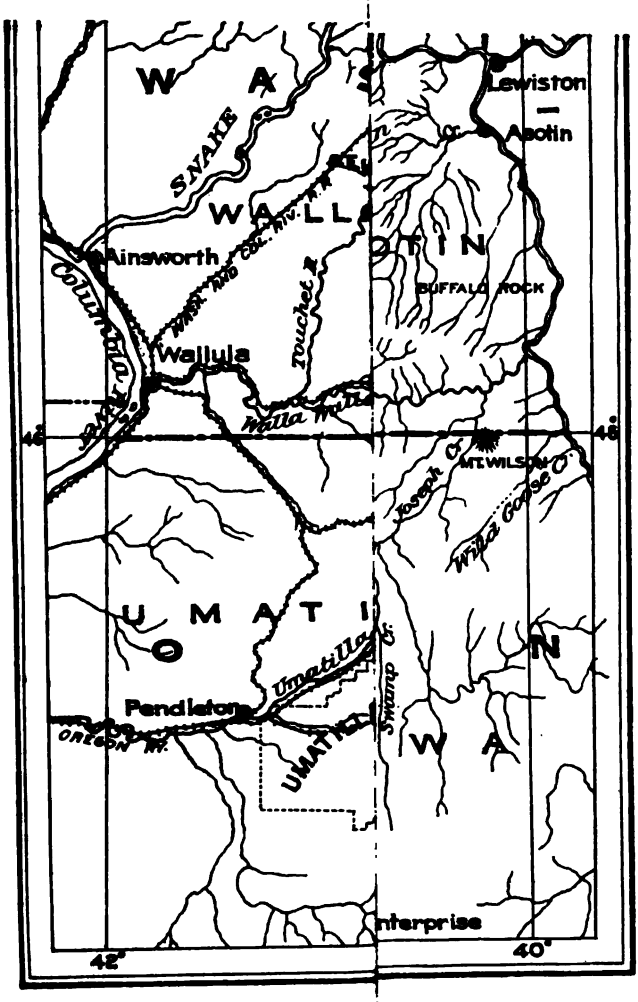
Mode of travel.—Southeastern Washington is largely a rich agricultural region. The cultivated lands are inclosed by wire fences, and roads have been laid out through the greater portion of it in a rectangular system governed by section lines. Farmhouses are numerous, except in the more arid western portion and in the Blue Mountains. The geological traveler has to take account of these conditions in planning his journey.

To facilitate my work and to be able to reach all parts of the region to be examined, I chose to "camp out." At Walla Walla I hired two men, Messrs. F. W. De Forest and A. C. Rud, to act as cook and teamster, respectively. We had a two-horse farm wagon, a saddle horse, tents, cooking utensils, etc. To one familiar with the vicissitudes of exploration in unsettled regions, camp life in southeastern Washington offers but few attractions. Nearly every night we camped near a farmhouse, and obtained hay for our horses from the farmer's barns, and in many instances wood for our camp fire from his wood pile. Our camps were of necessity at localities that could be reached with a wagon, but by making side trips with a saddle horse or on foot I was enabled to visit practically all localities that seemed to offer opportunities for gaining information concerning the geology of the country.

The accompanying map (Pl. I), on which the routes followed are shown in a general way, will serve to indicate to some extent how much of this report is based on actual observation and what degree of confidence can be placed in it.

CLIMATE.

The climate of south-central Washington, in the region about Pasco, for example, is decidedly arid. The annual rainfall, judging from weather records in neighboring towns, as Kennewick, Sunnyside, etc., must be less than 5 inches. To the east and west of this arid region a gradual increase in humidity is shown by changes in the character of the vegetation. The nature of the climate on the eastern portion


W A
SNAKE
Lewiston
Asotin
WALL
OTIN
Ainsworth
WASH. AND COL. RIV. R.R.
Columbia River
Touchet R.
BUFFALO ROCK
Wallula
Walla Walla
46°
48°
Joseph Cr.
MT. WILSON
Wild Goose Cr.
U M A T I
O
N
Umatilla
Swamp Cr.
Pendleton
OREGON RY.
UMATILLA
W A
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of the plateau which occupies nearly all of southeastern Washington is shown to some extent by the following weather records:[1]

Mean precipitation and temperatures for 1895.

Locality.	Precipitation.	Temperature.
	Inches.	°*F.*
Pomeroy	7.37	
Pullman	15.00	
Rosalia	13.69	45.6
Spokane	13.46	48.1
Walla Walla	14.89	53.1

The mean annual precipitation at Spokane for a period of fourteen years was 17.94 inches, the summer average being 6.77 and the winter average 11.17 inches. At Walla Walla, for a period of eight years, the mean annual precipitation was 16.80 inches, of which 5.96 inches fell in the summer season and 10.84 inches in winter.

The average annual rainfall throughout the eastern portion of Washington, over a belt of country about 50 miles broad and extending southward from Spokane River to the Blue Mountains, may probably be taken at 15 to 17 inches. Some years it is considerably less than this, as is shown by the records given above for 1895, and again may exceed this amount, which is assumed as a general average. Westward from this belt a gradual decrease is shown by the character of the natural vegetation, and by a decrease and final cessation of agriculture.

An interesting feature in the precipitation is the manner in which it is distributed throughout the year, and the nature of the rain and snowfall. Precipitation is greatest in December and January, and is then principally in the form of snow; July, August, and September are particularly rainless months. The rain usually falls gently. At no time, I have been informed, is it torrential, except at wide intervals, when what are termed "cloudbursts" occur. The fact that precipitation is normally in the form of gentle showers or snow is of vast importance to agriculture. The meteoric waters are absorbed and retained by the fine, deep soils, and do not gather in rills, except when the ground is frozen.

In winter, when the land is snow-covered, warm southwest winds, termed "chinook" winds, sometimes blow, and the snow evaporates and disappears rapidly without melting. This is unfavorable to agriculture, as much moisture is thus lost which would be absorbed by the soil if the snow were melted slowly. Again, in spring and summer,

[1] Compiled from the First Annual Report of the Bureau of Statistics, Agriculture, and Immigration [of the State of Washington], by J. H. Price, Olympia, 1896, pp. 22-24.

"hot winds" sometimes wither the grain, and then immense damage is done.

No measures of the rain and snow falling on the Blue Mountains have been made, but the precipitation in that section is known to be much more abundant than on the lower plateau to the north. I have been informed by persons familiar with the Blue Mountains that the snowfall in their higher portions frequently has a depth of 12 to 15 feet. In deep gulches and under the shelter of the forest it remains unmelted until late in the spring. It is this abundant snowfall that insures the permanency of the many creeks which flow from the mountains. Evidently, in a region where there is such a delicate balance between climatic conditions that admit of profitable agriculture and those that are accompanied by a failure of crops, care should be taken to preserve the forests on the mountains, for the reason, if for no other, that they prevent the blowing away of snow, and by sheltering it from the sun delay its melting.

The range in temperature and precipitation of southeastern Washington is shown by the following averages, by counties:[1]

Temperature and precipitation, by counties.

County.	Locality.	General elevation of cultivated portions.	Length of record, in years.	Number of stations.	Temperature.			Precipitation (rain and melted snow; inches and hundredths).		
					Mean annual.	Highest on record.	Lowest on record.	Average annual.	Summer average.	Winter average.
Columbia	Snake River Valley.	1,685	6	1	49.1	109	—15	27.77	9.12	18.65
Franklin	do	.....	2	1	.....	112	— 1	9.70	.....	.....
Garfield	do	1,600	4	1	52.1	100	— 2	13.93	5.80	8.13
Lincoln	"Big Bend"	1,600	10	1	47.4	105	—31	13.06	.....	.....
Spokane	East	1,900	14	1	47.5	102	—30	17.94	6.77	11.17
Wallawalla	Snake River Valley.	930	10	1	53.1	108	—17	16.80	5.96	10.84
Whitman	"Palouse"	.....	5	3	46.0	98	—19	18.21	6.73	11.48
Douglas	"Big Bend"	2,400	5	2	47.4	104	—30	12.70	.....	.....

VEGETATION.

In the western portion of the area represented on the accompanying map (Pl. I) the vegetation has the desert-like character found so commonly between the Rocky Mountains and Sierra Nevada-Cascade uplifts. Sage brush (Artemisia) growing in scattered clumps gives a monotonous, grayish-green tone to the desolate, treeless landscape. Of brighter green is the common greasewood, which is also familiar to

[1] First Annual Report of the Bureau of Statistics, Agriculture, and Immigration [of the State of Washington], by J. H. Price, Olympia, Washington, 1896, p. 22.

every traveler in the more arid portions of the West. Beneath these desert shrubs bunch grasses grow abundantly, unless eaten off by stock, and in early spring the ground is beautified by many lovely blossoms.

As one travels eastward and gradually rises to the summit of the basaltic plateau which forms the greater part of eastern Washington, the desert shrubs disappear and the hillsides and valleys alike are clothed with bunch grasses and are destitute of trees and shrubs. In recent years cattle and horses ranging over these seemingly boundless pastures have eaten off the nutritious herbage and made the land practically a desert.

Before the plateau of southeastern Washington was cultivated, the bunch grasses extended all the way to the mountains of Idaho. The surface of the plateau was then one vast, rolling prairie. The Palouse River, which drains a portion of the plateau, derives its name, it is understood, from the French word "pelouse," meaning greensward, lawn, etc., and is descriptive of the region as it existed for many years after the coming of the white man.

The forests still retain the regions they originally occupied, although inroads have been made with the ax. The Blue Mountains are covered with a varied and beautiful open forest of pines, spruces, and tamaracks, which are valuable for lumber. With these more important trees grow cedars, mountain ash, the haw, and a multitude of wild roses and berry bushes. Similar vegetation clothes the mountains of Idaho and extends down the water courses that enter the plateau region between Spokane and Snake rivers. A few of the buttes in the "Palouse country," which rise like islands through the basalt of the plateau, are also scantily clothed with pines and spruces.

Along some of the streams there are scattered growths of cottonwood, alders, elders, willows, and roses growing in dense thickets. The cottonwood, however, seldom reaches the large size and picturesque development that is seen along the Yellowstone and on the border of many other streams in the Rocky Mountains. The canyon of Snake River, like the valley of the Columbia in its middle course, is treeless. Above Lewiston, however, cottonwood and occasionally a pine appears, and in the canyon of Grande Ronde groves of pine along the river's banks and on islands in midstream, as well as in lateral gorges, give an additional charm to that wild and picturesque region.

Over nearly all of the agricultural portions of southeastern Washington wood of any kind is wanting, and all supplies for buildings, fences, fires, etc., are brought with much labor from the mountains. Wood and water are each highly prized in most of the agricultural regions. Water is frequently carried in tank wagons for a distance of 10 or 15 miles and stored in cisterns for domestic use and the watering

of stock. The conditions that have given large portions of Washington wonderfully rich and easily cultivated soils have been less favorable to man in other directions.

TOPOGRAPHY AND DRAINAGE.

Prevailing topographic features.—The portion of Washington lying to the south of Spokane River, together with what is termed the "Big Bend country"—a region in the central part of the State, bounded on the north and west by Columbia River—is, when minor features are disregarded, a great plateau. This plateau has been moderately disturbed by movements in the earth's crust which have caused elevations at certain localities and depressions at others; the uniformity of the surface has also been broken by stream erosion, and great canyons have been formed. The plateau is lowest in its southwestern portion, where the elevation above the sea, as at Pasco, is but 386 feet, and rises, particularly on its eastern border, to a general level of between 2,000 and 2,500 feet. The general slope in the region between Spokane River and the Blue Mountains is westward. In the absence of accurate topographical surveys, it is impossible to state just what is the slope of the general plateau surface, but from such information as is in hand a broad belt adjacent to the Washington-Idaho boundary appears to be but gently inclined. The chief portion of the descent from the eastern border to the depressed central region near the Columbia is due largely to erosion.

An exception to this general and very gentle westerly inclination of the plateau's surface occurs in the extreme south-central portion of Washington, beginning a mile or two south of Wallula, on the Columbia, and extending far into Oregon. In that region a large block of the originally level plateau has been tilted so as to incline gently southeastward. The Columbia below Wallula has cut a steep-walled canyon some 600 or 800 feet deep through this upraised region. Again, in what may be designated as the southeast corner of Washington, and extending far southward into Oregon, there has been another upheaval which has formed the Blue Mountains. These so-called mountains are essentially a low, flat dome, elevated about 2,000 feet above the general plateau surface. The uplift is so broad in comparison with its height that it is in reality a plateau, although now deeply dissected by stream erosion.

The reader will be greatly assisted as he reads the following pages if he will bear in mind that southeastern Washington, northward from the gentle uplift just mentioned, all the way to Spokane River, is a nearly uniform plateau, the general surface of which is inclined very gently westward. Over much of this vast region, embracing fully 25,000 square miles, and particularly in its eastern half, the country is so nearly level that no one on looking over it could distinguish any departure of the general surface from a plain. This

BASALTIC PLATEAU NEAR PULLMAN, WASHINGTON.

plateau is, as will be explained later, the surface of a series of horizontal basaltic lava sheets, and will for convenience be spoken of as the "basaltic plateau." On the east this plateau is bordered by the mountains of Idaho. The junction of the plateau with the mountains coincides in a general way, from Snake River northward, with the Washington-Idaho boundary.

The basaltic plateau is crossed from east to west by Snake River, which flows through a deep, steep-walled canyon. There are several streams that rise in the mountains of Idaho and in the Blue Mountains of Washington and Oregon which traverse the plateau in deep, narrow, trench-like valleys, which in fact are true canyons. There are also a few small streams which have their sources on the nearly level plateau and flow through deep valleys, which again are frequently canyon-like. Although the plateau has been deeply cut by the streams flowing across it, yet broad, flat-topped interstream spaces still remain to show what would have been the character of the entire region if it had not been deeply dissected.

Standing on the plateau between the branches of the various streams that have sunk their channels deeply into the rocks, the valleys, canyons, and ravines are concealed from view, and a limitless plain extends away to the horizon in all directions, or to the bordering mountains. In some regions, particularly in the "Palouse country," the surface of the plateau is roughened by short, rounded hills 50 to 80 feet high; but in a general view none of the hills are prominent, and they do not detract from the impression that the surface is essentially level. If one tries to travel in a straight line in any direction across the plateau, one soon learns that it has characteristics which are in marked contrast to its level surface. One may travel through the deeply sunken valleys and canyons for scores of miles, and in the case of Snake River Canyon for over 150 miles continuously, and be shut in at all times by walls of rock that seem like mountain ranges on either hand.

On the plateau's surface solid rock is not in view unless it is in the walls of some neighboring canyon. The soil is fine and deep, and not a pebble is to be seen. In the canyons the somber walls on either side are formed of the edges of thick sheets of basalt, and frequently columnar precipices rise tier above tier, each step being from 50 to 100 feet or more in height. The walls of the smaller canyons are in numerous instances from 500 to 1,000 feet high. The lateral canyons that join Snake River have a depth of 2,000 feet, that being the general depth to which that master stream has dissected the plateau from Lewiston nearly to its junction with the Columbia.

The views beheld on the uplands and in the valleys are thus as strongly contrasted as if they belonged to entirely different regions. As the railroads usually follow the valleys, a traveler is impressed with the prevalence of black basaltic rocks. In crossing the uplands,

the total absence of rock exposures over broad areas frequently leads one to wonder if solid rock actually exists at a moderate depth below the fine soil of the surface.

Where the general plateau rises to make the lower slopes of the Blue Mountains, and throughout that more elevated portion of the plateau, deep erosion has taken place, as well as deep rock disintegration and decay. The foothills of the Blue Mountains are rounded, and have beautifully curving outlines and contours. The first impression one gets on seeing these mountains from the north and west, as from the vicinity of Walla Walla, for example, is that they are composed of soft, easily eroded rocks. The similarity of the hills in slopes and general features to the forms assumed by elevations composed of unconsolidated clay or easily eroded shales, as they waste away beneath the beating of rain and are cut by rivulets and brooks, is so striking that one is astonished when one learns that the Blue Mountains are in reality composed of layer on layer of horizontally bedded basalt, a rock that is among the most resistant to mechanical wear of those commonly found on the earth's surface. As the reader will learn later, the basalt, although hard and resistant to forces tending to abrade it, yet yields with comparative rapidity to agencies which lead to disintegration and decay. The basalt in the region here considered weathers readily, and the loose products of disintegration are not carried away so rapidly as they are formed. A fine, soft, residual soil covers the land and imparts to nearly all its minor features the characteristic flowing outlines and gentle curves so common in regions where soft rocks alone occur. It is only in the canyons, even in the elevated and most completely dissected portion of the plateau forming the Blue Mountains, that the angular forms due to solid rock exposure attract attention.

The prevailing colors in the landscape to be seen on the plateau's surface, when not due to vegetation, are light yellowish-gray in the western part and dark brown—the color of rich humus soil—in the eastern portion. The bright reds and yellows so common in many regions of deep rock decay, especially where the climate is humid, nowhere meet the eye. Not a trace of the deep red so characteristic of the soils of Virginia, and of the southern Appalachian region generally, can be found in all of the deeply decayed surface of the basaltic plateau.

In a far-reaching view during the summer season over the surface of the plateau surrounding the Blue Mountains, except on the east, and also northward through Whitman and Spokane counties to Spokane River, the universal colors are brown and yellow—the brown of plowed land and the golden of wheat fields. The wheat lands as a rule are sown but every other year, so that practically half of the land lies fallow each summer. After the harvest, when the stubble fields are plowed and the soil is moistened with rain, the fields become

dark brown and appear almost black. In the canyons, where one is overshadowed and shut in by walls of basalt, the tone of the landscape is always somber, and frequently oppressive. The black walls of rock find but little contrast in the scant vegetation. The polished and shining stems of the bunch grass, however, which grows on every jutting ledge and smooth talus slope, frequently clothe the dark precipices with a silken garment of pearly gray.

Throughout the entire region from the Blue Mountains northward to Spokane River, and westward from the mountains of Idaho for 100 miles or more, the general features of the land are the same. The topography is young. The streams have not advanced far in their task of cutting away the rocks forming the plateau and of reducing the land to sea level. This appointed task, although well begun, has been delayed, and over the central and western portions of the plateau has been entirely checked by a decrease in rainfall. It is a relief to leave this region of broad plateau surface and narrow trench-like valleys—not only of young but infantile drainage—and visit the extreme southeastern corner of Washington, where a similar work has been carried on more energetically. The Snake River has there cut through the eastern flank of the Blue Mountain uplift and excavated a canyon about 4,000 feet deep and not less than 15 miles broad from brink to brink. An important tributary river, the Grande Ronde, rising in many branches in the Blue Mountains, has excavated an intricate series of branching canyons, the main trunk of which is as deeply sunken in the rocks as the magnificent gorge of the master river. In this region the topographic features were originally the same as in the less completely dissected portions of the lava-covered country, but for certain reasons the work of the streams is further advanced. The spaces between the streams are no longer flat-topped remnants of the plateau's surface, but the entire region bristles with sharp-crested ridges and is diversified in a wonderful manner with spires and pinnacles.

If a person climbs to the summit of one of the higher ridges and gains an elevation of about 3,000 feet above the canyons on either side, he will see that many other ridges rise to approximately the same heights and that what appears to be a group of sharp, angular mountains, separated by a labyrinth of canyons with silvery threads of water in their bottoms, is in reality a deeply dissected plateau. The topography is still young, although approaching maturity. The streams have not yet widened their valleys materially, but rapid decay has crumbled the walls between. The region treated in this report thus furnishes splendid examples of the various stages in the process by which a plateau is eaten away by streams. If space permitted, it would be instructive to take the reader to the mountains of ancient crystalline rock surrounding the basaltic plateau on the east

and north and point out the characteristics of a region that has long been exposed to the rain, sunshine, and frost, and from which the streams have been carrying their burdens of disintegrated rock for geological ages. We could thus learn what is meant by the term old topography. The forms of the original uplifts are lost, and only the remnants of once lofty mountains remain.

The bases of the old mountains were partially submerged by the overflow of molten lava that formed the plateau of southeastern Washington. The lava entered the valleys and gave them level floors of rock. Mountain spurs project into the plateau, like headlands along the ocean shore. Some of the old mountains, separated by erosion from their neighbors, were completely surrounded by the inundations of lava and now rise as islands above its surface. Steptoe Butte is an example of these ancient peaks which project through the lava of the plateau. These interesting features in the topography of the border land between Washington and Idaho will be better understood, however, after the character and origin of the basaltic rock of that region are discussed.

General characteristics of the drainage.—All of the lines of drainage in the portion of Washington here treated lead to Columbia River. The principal stream is Snake River, which flows across southeastern Washington from east to west in a deep canyon, which is the strongest natural boundary in the region. South of Snake River, all of the perennial streams rise in the Blue Mountains and flow in all directions, their courses being determined by the original slopes of the uplift. In the language of the geographer, these are "consequent" streams. All of them, as was stated in describing the general topographic features of the region, traverse deep gorges in the flanks of the Blue Mountain uplift, and in numerous instances, on gaining the less undisturbed plateau surrounding it, flow through deep canyons. The streams from the Blue Mountains, which are tributary to Snake River, join that stream in canyons that at their mouths are as deeply cut as the canyon of the main river.

Throughout the basaltic plateau north of Snake River the principal streams rise in the mountains of Idaho, and, with the exception of Spokane River, have their sources near the Washington-Idaho boundary. In crossing the basaltic plateau, the valleys and canyons of these streams sink deeper and deeper. The minor streams from the mountain are tributary to two rivers—the Palouse, which empties into Snake River, and the Spokane, which joins the Columbia before it makes its wide detour to the westward.

Besides the streams mentioned—which, however, include nearly all the perennial surface water in the portion of the basaltic plateau under consideration—there are minor streams, mere brooks, in fact, which rise in valleys excavated in the plateau when the rainfall was more abundant than at present, and are fed mainly by springs and the

general seepage from soil and rocks. The channels of many of the small streams are dry in summer, or their water may flow for a short distance, but fail to reach the main rivers. Some of these trunkless branches are indicated in the accompanying map (Pl. I), but as they are sensitive to minor climatic changes they vary materially in length from month to month, and almost from day to day, and can not be accurately plotted.

Snake River.—As already stated, the principal river of the southeastern portion of Washington is Snake River. With the exception of the Columbia, this is the only navigable river in Washington east of the Cascade Mountains. It has its source far to the eastward, in the vicinity of the Yellowstone National Park, and flows through southern Idaho. In what may be termed its middle course, for about 35 miles, it forms the boundary between Washington and Idaho, and then bends abruptly westward, where Lewiston is situated, and for 130 miles flows in a deep trench in the basaltic plateau to the Columbia.

At the southeast corner of Washington the canyon of Snake River is fully 4,000 feet deep, but below Asotin the height of its walls decreases, and thence to near its mouth it has a nearly uniform depth of 2,000 feet. The walls of the canyon are precipitous throughout, and in numerous instances are nearly vertical for a large portion of their height. This great gash in the rocks, of which the 160 miles below Mount Wilson is but a portion, has been worn by the river in dense, resistant rocks. The canyon walls throughout the region treated in this report are, with slight exceptions, formed entirely of the edges of horizontally bedded basalt. The weathering of the edges of the basaltic sheets has caused them to recede unequally and form steps or terraces in the faces of the precipices. Where the walls are steepest they present a series of narrow steps covered with soil and clothed with grasses, separating vertical rises of bare and frequently columnar rock, varying in height in most instances from 50 to 125 feet.

The canyon walls, to an observer from below, frequently appear to be nearly vertical, but the impression of their steepness gained from such a view is usually much exaggerated. Owing to talus slopes on the shelves and the fact that the escarpments of solid rock are frequently broken by side gulches, I think it is safe to say that nowhere is there a space half a mile in length up which one might not climb. Cattle and horses graze on the canyon walls in many places. Experience has made these animals nearly as sure-footed as goats, but bleached bones at the base of the precipice show that occasionally accidents happen to them.

The walls of the canyon are scored by steep lateral gulches, with buttress-like ridges standing between. Many tributary streams enter the canyon at the level of the river, and have curved and branching lateral canyons and gorges which extend away from the river 10 miles or more before gaining the surface of the plateau. The work performed by flowing water in excavating the numerous canyons and

valleys is impressive, and most striking examples of stream erosion meet one on every hand.

Snake River is a swift stream, the descent in the portion below Lewiston, as determined by the United States Engineer Corps, being 2.48 feet per mile, and is still engaged in corrading the bottom of its channel. Rapids due to solid rock occur at numerous localities.[1] Many of these obstructions have been removed for the purpose of facilitating navigation, but at low-water stages danger still exists. Steamboats have ascended the river from its mouth to Wild Goose Rapids, a distance of about 170 miles; but owing to numerous rocks and shoals below Riparia, where a branch of the Union Pacific Railroad now crosses the river, navigation is practically confined to the portion of the river which lies between Riparia and Lewiston. Other navigable reaches of the river occur above Wild Goose Rapids, but they are beyond the region under consideration.

Measurements of the volume of Snake River are not necessary to impress the beholder with the fact that it is an important stream. Its broad, swift current assures one that the waters of a vast region are there journeying to the sea. At the lowest stages the river is in general about 1,000 feet broad. Measurements made by officers of the United States Engineer Corps at Texas Rapids show that 26,000 cubic feet of water flow past during each second. When the snow is melting on the mountains of Idaho and Wyoming the river rises from 20 to 30 feet above its summer stage, and becomes a wild, rushing flood of muddy water. Its volume at such times must be in excess of 100,000 cubic feet per second.

As has been stated, the river is still deepening its channel. But little lateral erosion has taken place, and no general flood plain borders its shores. Where the river forms sharp bends, more particularly in the portion below Lewiston, there are frequently deposits of sand which rise a few feet above ordinary high-water stages. These "bars," as they are termed, are in some instances 200 or 300 acres in area. When planted with fruit trees and properly irrigated these light, sandy lands yield splendid crops of peaches, apricots, plums, grapes, etc. The warm climate of the canyon is especially favorable for fruit raising. Above Lewiston, where the canyon is deeper, and where certain changes occur in the character of the rocks inclosing it, the gorge is wider than where it crosses the basaltic plateau in its westward course, and the terrace-like lands in its bottom are of greater extent, although nowhere more than a few hundred feet broad.

An interesting episode in the history of Snake River Canyon is recorded by fragments of a high gravel terrace that occur in it. At

[1] In connection with the fact that Snake River is still deepening its channel, it is of interest to note that Columbia River is engaged in a similar task. At the head of the steep-walled canyon through which the Columbia flows, below Wallula, ledges of basalt cross the stream, but steamers can generally traverse the deeper channels. This obstruction is due to movements, apparently still in progress, in a large block of the basaltic plateau which has been uplifted across the course of the stream, and for a time caused it to spread out and form a large lake.

almost any locality on the bank of the canyon an observer will have in view, usually on the concave side of a curve in the river course, a terrace of coarse gravel and sand, the surface of which is about 360 feet above the stream. The descent from the flat surface of the terrace to the river is usually a smooth slope with an inclination of from 18 to 22 degrees. The canyon was at one time filled from side to side with deposits of the character shown in the terrace and to a depth recorded by the level of the deposits remaining. The river has since reexcavated its canyon, leaving fragments of the former filling at localities from which the current was deflected. The gravel and sand referred to show that the river, after excavating its canyon to its present depth, was checked in its rate of flow or so greatly overloaded that it could not carry away all the débris brought to it, and deposited its excess of load so as to raise its bed 360 feet. Subsequently, renewed energy, or a decrease in the supply of débris delivered to the river by its tributaries, allowed the stream to carry away the greater part of the material deposited.

The gravel deposit referred to extends into each tributary canyon. In such situations the lateral streams have cut modern channels through it, leaving terraces as in the main canyon. These gravel deposits are composed in part of worn and rounded fragments of basalt, but consist principally of quartzite, granite, and igneous rocks of older date than the basalt. The nature of this material shows that it was brought by Snake River from far up its course. The gravel was carried from the main canyon in some instances for several miles up the tributary canyons, as may be seen especially along Tokanon River at Starbuck, and checked the flow of the lateral streams. Small lakes were formed in some instances in the side canyons, owing to the abundant deposition of material at their mouths.

Terraces similar to the great terrace in Snake River Canyon occur along the upper Columbia on the border of Spokane River, and to a less marked degree in the canyons and valleys of the streams flowing from the Blue Mountains, showing that the widely extended influence which caused the streams to deposit a part of their loads affected a very large portion and probably the whole of the hydrographic basin of Columbia River at a comparatively recent date. The nature of the change which caused so many streams to partially fill their channels and then reexcavate them will be discussed later.

Walla Walla River.—This is one of the few streams having river-like proportions which rise within the region covered by the Columbia lava. Its various branches head in the northern and northwestern portions of the Blue Mountains and follow westerly courses. Their united waters, which enter the Columbia at Wallula, form a stream that in late summer has an average width of 50 to 60 feet, and discharges by estimate from 100 to 150 cubic feet per second. During high-water stages their volume is increased many fold.

In common with all other streams in southeastern Washington, the Walla Walla is clear except after rains, and furnishes wholesome water for domestic use. Where the many branches of the river leave the mountains they are especially clear, for the reason that they are supplied by infiltration, and all matter in suspension has been removed. The Walla Walla and its branches furnish instructive examples of what geographers term "consequent" streams—that is, streams which are directed in their course by the original surface slope of the land. As has been stated, the Blue Mountains are an upraised portion of the basaltic plateau. The uplift has the form, at the north at least, of a low, flat-topped dome, in which the rocks are horizontal except about the gently inclined margins. The general plateau surface to the northward, as already stated, slopes gently westward. The streams from the mountains radiate in all directions, but those which reach the lower plateau change their courses in obedience to the general slope of the surface in which they have sunken their channels. This is seen especially in Touchet River, the principal tributary of the Walla Walla from the north. This stream is formed by the union of several branches which start on the north side of the Blue Mountains and flow northward down the gentle slope of that uplift until the lower plateau is reached and then bend westward. The trunk stream of the Touchet has its direction determined by the westward slope of the plateau it traverses for 20 miles. This slope is not continued to the Columbia, however, but an upheaval of another portion of the tableland lying principally to the west of that river, and briefly described in the next paragraph, changes the direction of the Touchet and causes it to flow southward for about 12 miles before joining the Walla Walla.

Immediately south of Wallula is another block of the Columbia lava, which, as previously stated, has been gently tilted. The tilting is so moderate and affects such a large area that the edges of the lava sheets appear horizontal. The upraised area is bounded on the north by a line of cliffs near the Columbia. When followed eastward, these cliffs lose the precipitous character and change to hill slopes which die away, some at a distance of 20 or 25 miles. This line of abrupt change in slope probably indicates the presence of a break and the upheaval of the rocks on its southern border—that is, the uplift has been by faulting. In looking westward from the Blue Mountains, it is evident that the uplift just described has given a southeasterly slope to the surface of the country, which extends far southward into Oregon.

The Walla Walla River on leaving the Blue Mountains flows westward in a deep canyon, the direction of which was determined by the slope of the uplift. At the foot of the mountain it emerges as a surface stream, and is turned northward by the slope produced by the upheaval south of Wallula. Not only does the branch of the Walla

Walla, for which the name of the trunk stream is retained, behave in the manner described, but several other branches, of which Cottonwood, Russell, and Mill creeks are the most important, also become surface streams on leaving the mountains. These various branches, where they come together in the vicinity of Whitman, about 6 miles west of Walla Walla, are depositing the loads they carry during floods and building up their channels and flood plains. On account of the filling that is in progress, some of the branches, notably Mill Creek, divide, after the manner of a stream on its delta, and contribute their waters to the Walla Walla through two or more mouths. As one continues on down the Walla Walla to its junction with the Columbia, its channel grows gradually deeper and deeper, and below the mouth of the Touchet and near Wallula is certainly 50 or 60 feet below the general surface.

This abnormal behavior of the Walla Walla and its branches has led to legislative enactments which determine what proportion of the waters should be allowed to flow through certain of the bifurcating channels.

The manner in which the streams near Whitman are raising their channels so as to allow their waters to divide is a matter of much geographical interest, as it indicates that movements in the basaltic plateau are still in progress. The depressed region between the Blue Mountains and the smaller uplift to the west is probably slowly sinking. The rate of this subsidence is such that the streams are barely able to keep pace with it by grading up their beds. During high-water stages, I have been informed, expansions of the streams occur which resemble lakes. The expanded waters of the creeks are then united and much of the individuality of the various channels is lost.

The several branches of the Walla Walla furnish excellent sources of supply for town water and for irrigating purposes. In another section of this report the manner in which Mill Creek is utilized at the city of Walla Walla will be described. For purposes of irrigation, in order to make full use of the natural conditions, it will be necessary to store the winter run-off in the canyons of the Blue Mountains and hold it for summer use. If this can be done economically, a very large portion of the rich lands along the Walla Walla and its tributaries can be made many times more productive than they are at present.

Tokanon River.—This so-called river and its principal branch, the Pataha, rise on the north side of the Blue Mountains and enter Snake River through a deep canyon. The Tokanon and Pataha flow northward in their upper courses, their direction having been determined in their infancy by the slope of the surface, but before uniting they curve westward, in obedience to the gentle westward inclination of the plateau into which they have carved their channels. After the Pataha joins the Tokanon the latter flows west for 6 miles and then turns at a right angle on entering a gorge which leads it to Snake River. A

careful survey would probably show that the Tokanon in its youth continued to flow westward and became tributary to the Touchet, but that it was diverted at the present site of Starbuck by a small high-grade stream that flowed to the Snake.

The Tokanon at its mouth is but a brook in summer, across which one may step on the larger stones strewn along its channel without wetting one's feet. The Pataha was dry in its lower course when I visited its valley in August, and had shrunk back as far as Pomeroy. The canyons and valleys through which these two streams flow are deep and out of all proportion to the streams that occupy them. In its lower course the Tokanon is nearly 2,000 feet below the general level of the adjacent plateau. Many other examples of this nature indicate that the streams of the basaltic plateau were formerly larger and more numerous than at present.

Deadman Creek.—The creek with this doleful name, which, however, is suggestive of its own nearly terminated existence, is an exception to most of the streams of the basaltic plateau, for the reason that it does not rise in an elevated region, but is supplied in a feeble manner by the rains falling on a portion of the plateau that is almost completely cut off by deep canyons from all other portions. The deep, canyon-like valley through which it flows has a steep grade and many branches, some of which are now dry. Its catchment basin when the drainage was most vigorous was about 100 square miles in area, and the development of the streams had progressed until its numerous branches furnished a convenient avenue of escape for the waters that fell on every part. The stream in its days of vigor cut down its channel nearly to the present level of Snake River—that is, to a depth of about 2,000 feet—in the solid basalt. At present, as already stated, many of the once tributary valleys are dry and desolate, and the trunk stream is shrunken during the summer season to a mere rill. The soil throughout the valley is deep and rich, but there is no water for irrigation. The hillsides and the remnants of the plateau surface are also fertile, and fortunately absorb sufficient moisture from the light rains and winter snow to admit of their cultivation for wheat.

Alpowa and Asotin creeks.—The drainage from the northeastern slope of the Blue Mountains in Washington is conducted to Snake River through two channels, known as Alpowa and Asotin creeks. Each of these creeks rises in many branches on the slopes of the mountains, and all at first are surface streams, but on account of the cutting down of Snake River Canyon, into which they discharge, they have sunk deeply into the plateau and near their mouths have lowered their channels as rapidly as the master river. The Alpowa is little more than a brook in summer, but its waters serve to irrigate some 300 acres of orchard lands near where it joins the Snake. The Asotin is large and brings a never-failing supply of pure water to the

little town of Asotin. A costly irrigating canal is now being built for the purpose of conducting its water to a broad area of bottom land in Snake River Valley opposite Lewiston. Some account of this bold undertaking will be given on another page.

Grande Ronde River.—On the east side of the Blue Mountains the drainage is through a deep, wild canyon, which furnishes the finest scenery that can be found in southeastern Washington. The river that excavated this canyon is the Grande Ronde—or, as it is usually called by the inhabitants of that region, the "Grand Round"—a bright, swift, winding stream that is walled in on either side by precipices and mountain-like slopes 3,000 feet high. The canyon is not a narrow gash, for the upper portion of its inclosing walls have receded, and side streams, most of them temporary rills, have cut a multitude of steep, lateral gorges, between which outstanding buttresses extend far into the main gorge. In many places ridges that descend the opposite sides of the canyon overlap in its bottom and the stream makes sharp curves in order to pass around their extremities. The main tributaries of the Grande Ronde, like Joseph Creek, which is indicated on the accompanying map, have also sunk deeply into the basaltic tableland, as has each branch of these secondary streams. A great region that, but for the excavating power of the streams draining it, would be a flat-topped plateau, has been transformed into an intricate, branching system of sharp-crested ridges, with profound gorges and canyons between. The general height of the land has thus been reduced about 1,000 feet, but the sharp, angular mountains that have been sculptured out of the upraised block are so steep and their crests so narrow that their loss in actual elevation is scarcely appreciated.

The canyon of Grande Ronde throughout the lower 20 or 30 miles of its course is in general 2,700 feet deep. The distance between the "rim rocks" bordering its walls is from 8 to 10 miles. The great buttresses that start from the main walls, however, extend far out into the canyon and make its width seem much less than it really is. Throughout the entire region drained by the Grande Ronde the rock, as in the lower plateau to the north of the Blue Mountains, is basalt in horizontal sheets. Everywhere throughout the rugged walls that remain the horizontal courses of black basalt may be distinctly followed. A magnificent example is thus furnished of the dissection of an elevated plateau consisting of horizontal layers of hard rock by the slow process of weathering and stream erosion.

A peculiar feature in the topography of the canyon of the Grande Ronde, and one which adds greatly to the interest of its wild scenery, is the manner in which the spurs from the bordering mountain walls project into the gorge and overlap or dovetail. These lateral ridges decrease in height from the borders of the canyon toward its bottom until a height of about 1,000 feet above the river is reached; they are then prolonged at about the same level nearly across the

bottom of the canyon. The crests of the lateral spurs where they project far into the canyon are sharp and serrated and end in precipices. Between these interlocking spurs the river makes long bends and flows about these steep extremities in abrupt curves. The sharp, serrate ridges projecting from the north wall of the canyon frequently extend almost completely across the canyon and enter reentrant angles in the south wall. Between the cliffs forming the ends of these spurs and the precipitous and frequently apparently vertical south wall the river flows in a narrow, rocky channel.

It is impossible to describe briefly the peculiar topography of Grande Ronde Canyon so as to convey an idea of its ruggedness and of the many peculiarities due to the interlocking of lateral ridges just mentioned; but if we imagine the canyon as having been excavated to a depth about 1,000 feet less than at present and widened so as to be about 3 miles broad at the bottom, we shall have the general character of the upper gorge in mind. If over the nearly level floor of this wide-bottomed gorge we see the river winding from side to side, and at the ends of the southward curves cutting at the base of the cliffs bordering the valley on that side, and then fancy the region elevated a thousand feet, so as to give the stream renewed energy and allow it to cut a tortuous gorge in the bottom of the older valley, the ridges between the abrupt bends weathering to sharp crests and pinnacles, we shall be able to appreciate not only the characteristic features I have attempted to describe, but their mode of origin.

Two roads cross the canyon of Grande Ronde from north to south, but the excessive ruggedness of the canyon's bottom has thus far prevented the construction of even a safe bridle trail from east to west along the river.

Next to Snake River, Grande Ronde is the largest stream in southeastern Washington; but owing to the almost complete absence of bottom lands throughout that portion of its course which lies in Washington and for many miles south of the boundary, its waters can not be utilized for irrigation. Far south in Oregon the topography is different. Broad bottom lands there exist and the conditions are favorable for agriculture. Luxuriant bunch grass abounds, however, throughout the Blue Mountains and on the steep canyon sides. Stock raising is there the natural industry, but excellent fruit can be grown in all of the deeper valleys and gorges. In the gardens about the few houses and cabins that have been built by stockmen in the canyons of Grande Ronde and Joseph Creek vegetables of many kinds grow luxuriantly when properly irrigated, and tobacco plants as large and fine as any in Virginia or the Carolinas are now raised for domestic use.

Palouse River.—North of Snake River are a number of streams that head in the mountains of Idaho and flow westward in channels which increase progressively in depth, and finally become steep-sided canyons. The generally westward direction taken by these streams in

their infancy and retained as they excavated their valleys and canyons in nearly horizontal sheets of basalt was determined by the gentle westward inclination of the plateau—that is, they are consequent streams.[1] These streams unite to form Palouse River, a tributary of Snake River. This river was not examined during the reconnoissance which furnished the basis of this report, but is understood to be comparable with the Walla Walla in size. Symons states, in the report just referred to, that "the falls of the Palouse form another of the interesting objects of this section. In the lower portion of its course the Palouse flows through a deep fissure in the basaltic rocks, portions of which take fantastic forms, as towering pinnacles. At the falls the river descends perpendicularly for about 120 feet into a narrow basin, from which it flows off through its deep canyon for about 9 miles to the Snake River." The fall in the Palouse, whatever may be its history, is a marked exception to the even grade established by, I think, all associated streams, excepting Spokane River, and should claim attention, not only from geographers, but from those interested practically in water power and irrigation. The abrupt change from a westerly to a southerly direction that the Palouse makes in its lower course is perhaps due to a diversion of the river by the cutting back of a small high-grade stream flowing to Snake River. I fancy the falls have some connection with such a capture of the low-grade and comparatively sluggish river by a smaller but more energetic rival.

Owing to the presence of sheets of clay and sand interleaved with the basalt in much of the region drained by the Palouse, springs are numerous along its branches, and supplement in an important manner the drainage from the mountains.

The broad plateau surface adjacent to the "Palouse country" on the south and west has not been visited by me, but, as shown on the maps of the United States land survey, it drains westward. The feeble streams are frequently interrupted and small lakes are formed. The origin of these lakes has not been explained, but the suggestion is made that the streams occupy old drainage channels that have been partially filled with sand and soil derived from the adjacent portions of the plateau. These lakelets are apparently similar in many ways to Moses Lake, in the Big Bend country, which is held by a dam formed of drifted sand.[2]

Spokane River.—Like the Snake, this river heads in the mountains, well to the east of the basaltic plateau of southeastern Washington, and flows across it, much of the way in a deep canyon that has been excavated in horizontal sheets of basalt. As in the case of

[1] It has been suggested by T. W. Symons, in a Report on the Upper Columbia River, Washington, 1882, p. 116, that the streams here referred to have had their courses determined by glaciers which moved in the general direction that they follow. My observations failed to sustain this suggestion, as no evidence of the former presence of glacial ice was found anywhere in southeastern Washington.

[2] Bull. U. S. Geol. Survey No. 108, 1893, p. 96.

Snake River, also, the canyon of Spokane River was deeply filled with gravel at a recent episode in its history, and has since reexcavated its channel in part, making an inner steep-sided gorge in the gravels that fill the older and wider valley up to a certain level. When the stream renewed its work of excavation it did not flow in a straight course over its gravelly bed, but in curves. As the channel was deepened, projecting spurs of solid rock in the buried valley were discovered and had to be cut through before the modern gorge could be extended upstream. Some of the ledges of basalt that the stream met with as it progressed with its task of reexcavating have been cut through, but work is still in progress at one of them, as is shown at Spokane City. A curve in the course of the stream, when it began to clear out the gravels it had previously deposited, carried it across a buried ledge. This accident, as it may be termed, led to the growth of the thriving and beautiful city of Spokane.

A gauging station was established on this river at Spokane, Washington, in October, 1896, the gauge being at the bridge of the Oregon Railway and Navigation Company. The drainage area at this point is 4,005 square miles. A measurement made on August 27, 1896, by Mr. Cyrus C. Babb, when the water stood at a height of 2 feet, gave a discharge of 2,937 second-feet (cubic feet per second), while a later measurement, on October 17, 1896, at a gauge height of 1.46 feet, gave a discharge of 1,722 second-feet.

Precipitation formerly more abundant than now.—Throughout southeastern Washington there is abundant evidence that the rainfall was formerly greater than at present, and that the streams were larger and more numerous than we now find them. This is shown particularly in those portions of the plateau which are not crossed by streams flowing from the mountains to the eastward, as, for example, in the region with slopes leading to Deadman Creek, and over still larger portions of the plateau situated to the west and north of Palouse River. The valleys and canyons in the districts mentioned, while without question due to stream erosion, are disproportionally deep and wide in reference to the streams now occupying them. In many instances deep, trench-like valleys, such as streams are known to make, and which lead to similar valleys now occupied by water courses, are flat bottomed from side to side and entirely without drainage channels. Evidently in such instances there has been no surface drainage for a long term of years All the rain that falls is at once absorbed by the thirsty soil.

Similar evidence of a former period of greater humidity than the country now enjoys can be had throughout the basaltic region of southeastern and central Washington, as has been stated in a previous report.[1]

The time of the abundant precipitation, when the most marked of

[1] Bull. U. S. Geol. Survey No. 108.

what may be termed the secondary topographic features of the basaltic plateau came into existence, may for several reasons be considered as the Glacial epoch, when the higher mountains of Washington and Idaho were occupied by extensive snow fields and glaciers.

GEOLOGICAL FORMATIONS.

The geological problems presented in southeastern Washington are simple and easily understood. The rocks in this region fall conveniently in eight divisions. These are, briefly:

1. Crystalline and metamorphic rocks of unknown geological age, consisting principally of schists, gneisses, granites, and quartzites.
2. Dikes of igneous rock, which break through and are intimately associated with the metamorphic terranes just mentioned.
3. Coal-bearing sandstones and shales of Tertiary age, which form the surface at the eastern base of the Cascade Mountains and extend indefinitely eastward, may occur in southeastern Washington beneath the lava which forms the next group of rocks here enumerated.
4. Vast basaltic overflows, which cover all of the plateau region of central and southeastern Washington and extend widely into neighboring States. These rocks were poured out in a molten condition during what is known as the Tertiary period of geological history. This formation has been named the Columbia lava.
5. Interbedded with the sheets of basaltic rock composing the Columbia lava are beds of clay, sand, volcanic dust, and lapilli, which were deposited in part by streams and in part in lakes during intervals between the lava flows.
6. Above the Columbia lava in certain localities there are thick deposits of gravel, clay, and volcanic dust, constituting what is termed the John Day system. The rocks of this system were deposited in a Tertiary lake named Lake John Day.
7. In the canyons of Snake and Spokane rivers and along several of the more important secondary streams there are deposits of gravel and sand which were laid down by these streams after they had excavated their channels to their present depth.
8. As important as any of the rock groups just enumerated, but not usually classed as an independent geological formation, are the soils. Reference is here made especially to the deep, rich soils that mantle practically the entire surface of the Columbia lava. These soils are almost entirely a product of the disintegration and decay of the underlying basalt and represent what are termed residual soils. Mingled with the residue left by the decay and partial solution of the basalt is a minor quantity of volcanic dust which was blown out by some distant volcano and scattered widely over the land by the wind.

Each of the rock groups briefly enumerated extends far beyond the region treated in this report, and in part has been described in a previous publication.[1]

[1] Bull. U. S. Geol. Survey No. 108.

METAMORPHIC ROCKS.

In the report on a geological reconnoissance in central Washington, just referred to, there is a brief description of the crystalline rocks occurring in the mountainous region north of the Big Bend of the Columbia. From what little is known of the geology of northern Washington and western Idaho, it seems evident that this same great system of granites, schists, quartzites, etc., not only forms the mountains bordering the basaltic plateau, but to a considerable extent the floor beneath it. These ancient crystalline rocks were elevated into mountains and deeply eroded before the Columbia lava was poured out. The deep trench carved in the basaltic plateau by Snake River has revealed the underlying rocks at three localities.

Gneiss[1] *at Granite Point.*—The first exposure of metamorphic rock met with on ascending Snake River is about 24 miles below Lewiston and is known as Granite Point. The rock in the bottom of the canyon at this locality is granitic in character and is what is known commercially as "granite." More strictly speaking, however, it is a gneiss—that is, a rock having the same mineralogical composition as granite, but in which the minerals are arranged in bands and folia. The rock is dark in color, owing to the abundance of black mica scattered through it in irregular bands.

At Granite Point this rock is exposed on each side of the river for a distance of about 1,500 feet and rises to a height of 160 feet above the water. The canyon walls, rising fully 2,000 feet above the gneiss, are composed of the edges of horizontal sheets of basalt, and show the minimum depth to which the summit of the ancient hill, perhaps a prominent feature in old topography, was buried by the basaltic overflows.

The gneiss has been opened by quarrying to a depth of a few feet, but it is of dark color, of rather coarse texture, and has a foliated structure, which will probably preclude its use as a building stone except for rough masonry, such as the abutments of bridges, foundations, etc. The rock is fresh in appearance, and no products of disintegration mantle its surface. Evidently the portion exposed is the summit of an elevation from which, previous to the inundation of basalt, loosened fragments were carried away as rapidly as they originated. Both up and down stream from Granite Point for scores of miles the walls of the canyon are composed from bottom to top of horizontally bedded basalt. Downstream, however, especially on the left bank of the river, a westerly dip in the lower sheets of basalt, amounting to perhaps 2 degrees, can be detected. This is one of the few instances throughout the basaltic plateau to the north of the Blue

[1] The designation of this rock as a gneiss is from field notes and is provisional. There are reasons for believing it to be a quartz-diorite, and therefore igneous and not metamorphic in origin. This same remark applies also to the rock occurring at Granite Point, a few miles south of Pullman, mentioned on page 37.

Mountains in which any departure of the lava sheets from a horizontal position has been observed.

Schists at Buffalo Rock.—About 15 miles up the Snake River from the town of Asotin there is a locality known as Buffalo Rock,[1] which is of special geological interest. This locality can be reached conveniently from Asotin by following a road recently opened along the west side of the river and at the bases of the great precipices of basalt that form the canyon walls. Above Asotin the canyon of Snake River is deeper than below that locality and furnishes many striking exposures of columnar basalt, which rise tier on tier to a height of over 3,000 feet. In the neighborhood of Buffalo Rock, however, an important change occurs. The metamorphic rocks which formed the surface of the country before the vast inundation of molten lava took place again appear above the level of Snake River and rise at least 2,000 feet into the horizontally bedded basalt. The river has cut its gorge across a buried mountain so as to expose the rocks composing it for about a mile on each side of the stream. The horizontal layers of basalt abut against the steep sides of the old mountain and show no evidence of disturbance at the contact. It is evident that the lower rocks have not been forced upward into the basalt, but that the latter was poured out in successive sheets and flowed about a mountain of schist and finally overtopped its summit and buried it from sight. Additional overflows of the same character were spread over the site of the buried mountain and reached a thickness of fully 1,000 to 1,500 feet above its summit before Snake River began to excavate its canyon.

The sides of the buried mountain, where they first appear above the river, are steep and without talus slopes or other products of disintegration. Although 3,000 feet of horizontally bedded basalt are exposed in the canyon walls adjacent to the outcrops of schist, it is evident that the valleys of the old land lie below the level to which Snake River has corraded its channel.

Where the schists rise from the river and form the lower portion of the canyon walls, marked changes occur in the topography of the profound gorge. The horizontal lines and bands formed by the edges of lava sheets give place to apparently structureless walls, which are extremely precipitous. The schist is more resistant to atmospheric agencies than the basalt, and the gorge cut in it is narrow. Vertically above the schist the canyon widens, so as to make reentrant angles in its general course. This increase in the width of the gorge above the schist is especially conspicuous when viewed from its borders.

The rocks which cause these important changes in the character of the canyon are mostly greenish, spotted schists, and are evidently

[1] The name, I have been informed, refers to certain rock inscriptions made by Indians, some of which are thought to represent buffalo. A large rock on the west side of the river is covered with figures made by pounding the surface with a dull instrument, probably a pebble. Similar designs are said to occur also on the rocks of the opposite shore.

of sedimentary origin, as well-rounded pebbles and angular masses of rock may still be recognized in them. Samples may be collected showing a transition from conglomerate, in which the pebbles are still prominent, through schistose rock containing flattened and elongated pebbles, to greenish schist with spots and blotches due to altered pebbles, and from these, again, to fine, even-grained, silky schists of uniform color. Near the southern end of the exposure there are rocks of plutonic origin[1] which appear to be dikes breaking through the schist, but as a similar rock occurs as pebbles in the schist, it is evident that at least some of the intrusives were formed before the material since metamorphosed was deposited.

The schists are traversed by small veins of quartz, which are probably gold bearing, as gold is obtained by placer mining in the gravels and talus slope bordering the river. What success has attended these mining operations I was unable to learn during my brief visit. No true fissure veins were seen in the schists, and from such examinations as I was able to make it seems doubtful if quartz mining will ever be profitable.

Schists at Wild Goose Creek.—Upstream from Buffalo Rock one may follow the river by a bridle trail to beyond the mouth of Grande Ronde River, a distance of about 8 miles. Throughout this portion of the canyon the walls are precipitous, frequently rising in sheer cliffs, and are composed from base to summit of horizontally bedded basalt. The canyon walls increase in height as we ascend the river, and at the mouth of the Grande Ronde are about 4,000 feet high. The actual margins of the canyon, however, recede from the river, and it is only when one gains a commanding point on the rim of the vast gorge, like the summit of Mount Wilson, for example, that its full grandeur is revealed.

Just above the mouth of the Grande Ronde metamorphic rocks again rise above the level of the river and form a large part of the canyon walls for at least a score of miles. The full extent of this fine exposure is not known, but it is prolonged far to the south of the southern boundary of Washington. The metamorphic rocks appear suddenly above the level of the river at a locality about a mile south of the mouth of the Grande Ronde, and rise from the water in what appear to be vertical precipices to a height of approximately 2,500 feet.

The leading phenomena presented at Granite Point and Buffalo Rock are here repeated, but on a grander scale. The horizontal basalt abuts against cliffs of schist, and shows no change at the contact. The sides of the buried mountain range, as seen in section in the canyon walls, are precipitous. On the east side of the river, where the schist first appears as one journeys upstream, the buried

[1] Thin sections of this rock have been examined by Mr. J. S. Diller, who states that it is a porphyry, composed chiefly of granular quartz with much biotite, forming a groundmass in which are embedded phenocrysts of quartz and feldspar, chiefly plagioclase.

mountain side slopes about 45°, and is free of débris. The base of the mountain is evidently far below the level of Snake River. Each successive layer of basalt extended farther and farther over the metamorphic rocks, until at a height of about 2,500 feet the summit of the range is covered. The horizontally bedded lava above the highest peak of the buried mountain is not less than 1,500 feet thick. A clear section of fully 4,000 feet of horizontally bedded lava sheets is there exposed, but the base of the pile is not seen.

The metamorphic rocks that appear beneath the basalt between the mouth of Grande Ronde River and Wild Goose Creek were only hastily examined, and attention can only be given at this time to their more general features.

The rocks are plainly of sedimentary origin, as their stratification is prominent. They have a thickness of several thousand feet. The strata in the northern part of the section are inclined northward at an angle of 40° to 45°, and in places are nearly vertical. A great dome of ancient rocks has been cut through. The upper layers of the dome are thin-bedded siliceous limestone containing indefinite fossils;[1] beneath this are thick layers of thinly laminate, granular limestone, containing some silt and organic matter, which appear in conspicuous white ledges. This rests on schists that show a diversity of colors, varying from green to red, and are frequently fine and silky in appearance. Marked contrasts are apparent in the schists, some layers being schistose conglomerates or breccias, while others resemble the finest roofing slate. The schist has great thickness, and is believed to rest on granite. The lower contact of the schist was not seen, but granite occurs abundantly in the pebbles along Snake River, and is reported by miners to come to the surface a short distance above Wild Goose Creek. The topography in that region bears out this statement.

No more than a hasty outline of the character of the rocks here referred to is possible at this time, as my opportunities for observation were, for several reasons, very limited. It seems evident, however, that a broad uplift, with a granite core, passing upward into schist and then again into but moderately altered limestones, was buried beneath the basalt and again exposed and deeply dissected by erosion. The geologic age of the schists and limestone is unknown, but a careful search in the limestone would very likely reveal fossils by which it might be determined.

Standing on the summit of Mount Wilson, which is a remnant of the basaltic plateau left isolated by the cutting of the canyon of Snake

[1] Samples of this limestone have been studied by Mr. J. S. Diller, who reports that thin sections examined under the microscope "do not show fossil forms nearly so distinctly as the weathered surfaces. The specimen was shown to Mr. G. H. Girty, and he agrees with me not only that the fossils are crinoids, but that one of them has a pentagonal stem. Crinoids with stems of this sort are not definitely known to be older than the Permian, and it is probable that this one is considerably later. The specimens examined look very much like the Triassic limestone of California, in which fossils are abundant."

River and the much narrower but nearly as deep gorges of Joseph Creek and Grande Ronde River, one may command a far-reaching view of the deeply dissected region about, and may read the leading facts in its geological history as plainly as from a printed page.

Eastward from Mount Wilson one beholds the deepest and wildest portion of Snake River Canyon. Fully 50 miles of the great gorge are in full view. To one familiar with the narrow, trench-like character of the same canyon for 100 miles or more below Lewiston, it is at once apparent that marked variations in nearly all its features accompany the change produced by the unearthing of the buried mountain range already briefly described. The canyon is deeper, also, than farther downstream, for the reason that Snake River has here cut across the flank of the Blue Mountain uplift. Where the metamorphic rocks form a large portion of the canyon walls the excavation is probably four or five times as wide as where it is cut wholly in basalt. The distance from the remnant of the old plateau surface forming Mount Wilson across the canyon to the fringe of pines growing on the crest of the opposite wall is, by estimate, fully 15 miles. In this interval there is what seems at first a bewildering maze of mountain-like ridges, palisades, towers, and battlements. Many of the forms are strikingly architectural in appearance. Vast buttresses of schistose rock, rising precipitously from the depths of the canyon, form the basements of huge castle-like masses of basalt, in which the horizontal bedding resembles courses of cyclopean masonry. The student of topographic forms sees at a glance that not only the more prominent features of the rugged landscape, but the details in the sculpturing of the seeming castles and palaces conform to well-known laws of erosion, weathering, and rock structure. In the upper portion of the canyon walls the horizontal bands formed by the edge of lava sheets may be traced on either hand as far as the eye can reach. Many of the lava sheets are columnar. The long colonnades, lessening in perspective, may be followed into each alcove and lateral gorge, and far out on the buttressing ridges. At the ends of many of the spurs there are groups of towers and pinnacles formed of the ruins of isolated masses of columnar rock.

Below the basalt are sharp crests and ridges rising between lateral gorges that lead down from the battlements above to the silvery thread formed by the river in the depths below. In the lower portions of the canyon walls, where schists and granite are exposed, the prevailing lines are vertical, and are due to the erosion of lateral streams and rills. Where the lateral ridges approach the river they end in precipices, which frequently descend nearly vertically for a thousand feet to the water's edge. At such localities there is no room for one to pass between the river and the towering cliffs. It is the abruptness with which the lateral spurs plunge down to the river that gives the vast gorge much of its canyon-like character.

In breadth and depth and in the multitude of details this canyon is comparable with the greatest of all canyons in North America, namely, the Grand Canyon of the Colorado. One of the greatest charms in the wonderful scenery of the Colorado, however, is wanting in Snake River Canyon, namely, the varied and brilliant coloring. The canyon of Snake River is dark and somber. The black and brown of weathered basalt and the dull gray of schist and granite find scarcely any relief from brighter colors. The pleasing tints imparted to the scenery of many regions by the iron oxides in residual soils are absent. The vegetation is too scanty to mask the angular forms or enliven the somber tones of the rocks, although the massive cliffs are in places veneered with yellow lichens, and in the lateral gorges, where springs well out, there are faint lines of verdure. In autumn these thickets of willow, haw, and roses assume brilliant hues. The talus slopes between the horizontal cliffs of basalt, as well as the surfaces of the ridges and domes of schist and granite, are clothed with bunch grass, which gives to them a silvery sheen that is ever changing when the wind blows.

On looking across Snake River Canyon from the summit of Mount Wilson, the junction of the horizontally bedded basalt with the schists and granite beneath can be distinctly traced for a score of miles. The crest line of the buried mountain is rugged and serrate. The gorges between the higher crests and spires are filled with horizontal sheets of basalt, showing that the fiery flood flowed about the ancient peaks, leaving them for a time as islands in a sea of molten rock, and then overtopped their summits and completely buried them from sight. This impressive spectacle of what was once a sharp-crested mountain range, rising at least 2,500 feet and probably more than 3,000 feet above the adjacent valleys, and subsequently buried beneath horizontal sheets of molten rocks, and ages later revealed by the slow down-cutting of a river canyon, is one of the most instructive lessons that the student of geology and geography will find anywhere in the world.

Glancing westward from Mount Wilson into the magnificent canyon of Grande Ronde, which has been excavated in the Blue Mountain uplift, one sees at least a thousand feet of horizontally bedded basalt which lies above the level of the summit on which one stands. The Columbia lava is, therefore, not less than 5,000 feet thick. Of its maximum thickness we have as yet no measure.

But to return to the metamorphic rock. No granite was found by me in the canyon of Snake River; but, as already stated, it is reported to occur a little above the mouth of Wild Goose Creek—that is, to the south of the point where the Washington-Oregon boundary meets the river. In the canyon walls, as we have seen, the basalt is clearly distinguishable from the rocks beneath it. The schists also have topographic forms of their own, in which the bedding, now highly inclined, and the joint planes play an important

part. As the eye ranges along the cliffs bordering Snake River upstream from the mouth of Grande Ronde, a marked change is apparent in the sculpturing of the older rock-series a few miles south of Mount Wilson. The sharp crests and steeply inclined bedding planes of the schist there give place to rounded domes and hillocks. The immediate banks of the river are precipitous, but at a height of perhaps a thousand feet above the water the slopes are more gentle, and a rude terrace with rounded curves and flowing outlines, some 3 or 4 miles broad, leads to the cliffs of basalt which define the upper margin of the canyon. The forms seen on the terrace-like slopes are such as are familiar in many localities where granite is the surface rock and where weathering is far advanced. Further exploration in this interesting region will probably show that the series of limestone, schist, etc., already briefly described, rests on granite, and that for many miles along the boundary between Oregon and Idaho this rock will be found in the immediate banks of Snake River. I have spoken of the rocks beneath the basalt as belonging mainly to the metamorphic series, but whether this granite is a sedimentary rock changed by heat and pressure or is of igneous origin I leave others to discover.

The schists exposed in Snake River Canyon, like the similar rocks a few miles farther downstream, are traversed in every direction by small segregated quartz veins, which have been reported to be gold bearing. Several mining claims have been located along the canyon wall on each side of the river, but whether any of these will repay mining is not known. From a knowledge of similar rocks elsewhere the value of these mines seems doubtful. In the alluvial deposits along Snake River at the mouths of lateral gorges in the schists, placer mining has been carried on from time to time for several years. Hydraulic mining on a small scale has been attempted, but with what success I am unable to state.

Granite, schist, quartzite, etc., north of Snake River.—The eastern boundary of Washington to the north of Snake River cuts across the foothills of the mountains of Idaho, leaving some of the ridges and outstanding buttes to the west of the line. The geology of western Idaho is as yet unwritten, but, as shown by the sand and gravel in the streams which enter Washington, the rocks to the eastward include granite, gneiss, quartzite, diorite, etc. Mountains consisting largely of these rocks form the eastern limit of the overflows of Columbia lava in the region here considered. The great basaltic plateau meets the mountains in a sinuous line which in a general way coincides with the interstate boundary. The mountains along this boundary resemble a rugged coast line, but the sea is replaced by the plateau of lava. Rounded and weather-beaten capes and promontories on the shore of the lava sea project into the wheat lands of the plateau and a few islands of quartzite break the monotony of its surface.

To term the rolling prairie lands of the "Palouse country" a sea and the hills to the eastward its rugged shore is not entirely a rhetorical

figure. The basalt forming the vast plateau was once molten and flowed over the land in successive inundations of liquid rock. The plateau was then a sea of fire. As sheet after sheet of molten rock was spread out, the floods rose higher and higher on the rock-bound coast. Valleys and embayments in the mountains were flooded and now have level floors of basalt. The eastern limit of the region covered by these fiery inundations is sharply defined not only by the topography but by the junction of the wheat fields which flourish on the soil formed by the decay of the lava with the uncultivated uplands.

The lavas are less deep in the neighborhood of the mountains than farther westward, and at one locality at least have been cut through by stream erosion so as to expose the granitic rocks beneath. At what is known as Granite Point, on the Northern Pacific Railroad, about 8 miles southeast of Pullman, in township 13, range 6, a few hundred square feet of gneiss (?) may be seen in the bottom of a shallow valley. This rock has been quarried in a small way and found serviceable for rough masonry. It is somewhat weathered, but the usual products of long-continued disintegration and decay are absent. The shape of the rock surface exposed and the absence of débris on it suggest that it is the summit of a hill from which all loose material had been removed before the floods of lava buried it from sight. The rock at this locality is of the same character as that already mentioned as occurring at Granite Point, in Snake River Canyon, about 10 miles distant. The difference in elevation between these two exposures of the old land surface beneath the basalt is approximately 2,000 feet. This is one of many observations which indicate the roughness of much of the country which was changed to a level plateau by the basaltic overflows.

The most striking evidence, however, of the ruggedness of the topography of the buried land and of the ocean-like character of the inundation of molten rock that flowed over it is furnished by the old mountain peaks, that now rise as islands above the yellow wheat lands. These islands are within a few miles of the border of the basaltic overflows. All of the old landmarks where the basalt is deepest are completely buried. Islands of granite surrounded by basalt, near the northern border of the plateau, in the neighborhood of the Grand Coulée, in the Big Bend country, were described in a previous report[1] but far more impressive examples of the same general character are furnished by Kamiack and Steptoe buttes in the Palouse country.

Kamiack Butte.—In Whitman County, 9 miles north of the town of Pullman, there stands a picturesque hill of quartzite and of quartzose conglomerate rising 500 or 600 feet above the surface of the surrounding basaltic plateau. This is the summit of a bold hill that was completely surrounded by the inundations of molten rock.

[1] Bull. U. S. Geol. Survey No. 108, 1893, p. 90.

The soil on Kamiack Butte is sandy and was derived from the disintegration of the underlying rock. It differs in a marked way from the soil of the adjacent wheat lands. There is no evidence to show that the basalt ever covered the butte, although it rose between 100 and 200 feet higher than the present plateau surface. The lowering of the surface of the plateau is due to the disintegration and decay of the basalt and the removal by stream and wind erosion of some of the fine soil thus produced. It is an instructive fact, as will be noted in advance in considering the origin of the low hills of the originally level plateau surface, that the soil of the plateau has not been blown over the rocks forming the butte.

To the southwest of Kamiack Butte and about 2 miles distant is another but lower elevation of the same character. To the eastward, also, there is a range of hills, apparently composed of quartzite, which extends into Idaho, and is of the nature of a cape projecting into the sea of formerly molten rock. The extremity of this ancient headland is separated from Kamiack Butte by 2 or 3 miles of basalt.

Steptoe Butte.—This remarkable feature in the relief of eastern Washington is situated in Whitman County, 8 miles west of the town of Garfield, and 10 or 12 miles from the hills which bound the basaltic plateau on the east. It rises between 1,000 and 1,100 feet above the plateau which surrounds it on all sides. From every direction, over a wide extent of country, the butte is a prominent landmark, and from whatever point of view it is seen it appears as a steep-sided and sharp-pointed pyramid. When viewed from the eastward, its southern slope makes an angle of 18° and its northern sides an angle of 19° or 20° with a vertical line. Each side is gently concave and gives to the eminence the appearance of a volcanic cone. The slopes on all sides except the west, which is easiest of ascent, are about as steep as is shown by the measurements just given.

Steptoe Butte, like its lesser companion described above, is composed mainly of quartzite, but at the summit the rock has the character of a quartz-schist. Its sides are not encumbered with loose débris, and but little soil has formed from the disintegration of the hard, resistant rock. It is plainly the summit of a bold mountain peak, the base of which was deeply buried by the overflows of lava that surrounded it and left it as an island.

The instructive panorama spread before an observer on Steptoe Butte leads naturally to a digression from the study of the geology of the butte itself. From this commanding summit we can with advantage, I think, review some of the leading features in the geography of the region under consideration.

To accommodate tourists, a commodious hotel has been built on the apex of the great pyramid. From about the hotel we may in an hour obtain a far more graphic idea of the characteristics of the surrounding region than days of travel across the plateau and over the neigh-

boring mountains would furnish. In all directions from the base of the butte extend the vast wheat lands of the basaltic plateau, which are seemingly as level as the sea. The short hills and level-floored depressions on the surface of the plateau enhance rather than detract from this resemblance. It is a stormy sea, but none of the wave-like hills rise above a certain general level. The distant horizon is undulating, like the sky line on the ocean after a storm. The view to the north, west, and southwest is limitless. Not a single landmark rises above the general level of the roughened plain. Far away to the south a long, low arch, forming a silhouette in blue against the sky, reveals the outline of the Blue Mountains. The base line of the arch is 30 or 40 miles long, and the height of its crest not over 1,200 or 1,500 feet above the general level of the intervening plateau. We know that in the vast plain that extends to the Blue Mountains there is a deep canyon through which Snake River flows, but it is only under exceptionally favorable conditions of the atmosphere that its course, easily mistaken for the shadow of a passing cloud, can be traced through the yellow wheat fields. To the eastward one sees the dark forest-covered hills and mountains of Idaho, and can trace the sinuous line formed by the junction of the intervening plateau with the highlands that determine its border. Each level-floored inlet and embayment is yellow with grain and each headland dark with pines. These and other features of the border of the once molten sea of lava can be as easily recognized as the inlets and headlands of the coast of Maine when viewed from the summit of Mount Desert Island.

Before the rich soil of southeastern Washington was furrowed by the plow it was covered with bunch grass, but destitute of trees and shrubs. At present practically every acre of the plateau surface is under cultivation. The observer on the summit of Steptoe Butte looks down on a limitless patchwork of brown and yellow. The brown is the soil of fallow land, the yellow the golden of the wheat fields. It is the custom to take but one crop from the land in two years, so that each summer practically half of the land lies fallow. The yellow grain fields and the brown, plowed lands are interspersed with each other as far away over the plateau as the eye can reach. Although there are thousands of farmhouses in the field of view, they are nestled in valleys and hollows, and only a few near the immediate base of the butte are in sight.

Next to the boundless expanse of the level plateau, the most interesting feature of the landscape is furnished by the wave-like hills and streamless depressions that give diversity to the grain fields. When I visited Steptoe Butte late in September the wheat had been harvested, and the paths of the reapers surrounded the hills like the contour lines on a map and served to accent the peculiarities of their forms. The origin of the hills, however, and the nature of the deep,

rich soil of which they are composed can be better understood from a nearer inspection and will be discussed later. Let us now return to our study of the ancient crystalline rocks.

The uplands, consisting largely of quartzite and granitic rocks which occur north of Snake River along the general course of the Washington-Idaho boundary, swing westward near Spokane and form the mountainous region of northeastern and northern Washington. This region is known in an indefinite way as the "Okanogan country." As described in Bulletin No. 108, the Columbia River in making its wide detour termed the "Big Bend" follows the base of the mountains that determine the northern border of the basaltic plateau. The same great series of crystalline rocks is continued westward and forms the mountain about Lake Chelan and the northern part of the Cascade range. Much of this region of crystalline rocks is rich in minerals, and excellent building stone abounds. This most promising field for geological study awaits exploration.

KITTITAS SYSTEM.

In west-central Washington, notably in Kittitas County and crossing the Columbia at Wenatchee, there is an important system of sandstones and shales carrying valuable beds of coal, which rests on the series of ancient crystalline rocks described above, and is covered in part by the lavas next to claim attention. The coal mines at Roslyn are in this system.

In Bulletin No. 108 I have proposed the name of Kittitas system for these coal-bearing rocks, for the reason that they form the surface over a large part of Kittitas County. The rocks of this system have not been studied and their boundaries are unknown, but in the central part of Kittitas County they pass beneath the series of lava sheets forming the basaltic plateau of central and southeastern Washington, and may possibly extend beneath the region described in this report. No outcrops of the rocks of the Kittitas system are known, however, east of the Columbia, except in the neighborhood of Wenatchee, but it is not improbable that they extend somewhat widely beneath the lava rock of the central basin.

COLUMBIA LAVA.

As already stated, the great basin between the mountains of Idaho and the Cascade range, including what is known as the "Big Bend country," or the Great Plains of the Columbia, and all of the southeastern portion of Washington, is covered with what is termed, in a general way, lava rock. Since a convenient geographical name for this lava is desirable, I have suggested the term "Columbia lava," for the reason that much of the country covered by it is drained by the Columbia River and its branches.[1]

Origin.—The Columbia lava was poured out from openings in the

[1] Bull. U. S. Geological Survey No. 108, 1893, p. 21.

earth's crust in a molten condition, in much the same manner that volcanoes at the present day are discharging similar material. It probably came from fissures in the earth's crust, however, instead of from individual vents, as in the case of Mount Rainier, for example, and spread away from the fissure in highly liquid sheets, which flowed rapidly.

As is shown wherever canyons have been cut in the Columbia lava, it is not one vast flow, but is composed of many beds, frequently from 50 to more than 150 feet in thickness, which are separated by scoriaceous layers and other partings. The surfaces of flows which cooled before the next sheet above was poured out are frequently rough and of a cellular or scoriaceous character and are occasionally covered with lapilli, as well as with widely extended layers of clay and sand and old soils.

The statement that the lava was poured out through fissures is based in part upon an hypothesis which is held for the reason that the features characteristic of volcanoes are absent and no plausible account of the origin of the lava, except by "fissure eruptions," has been suggested. The fissures through which the lava is supposed to have reached the surface would be filled with similar material and would give origin on cooling to what are known as dikes. At one locality in Kittitas County, where the rocks beneath the lava have been exposed by erosion, large dikes of this nature have been seen.[1] This observation is in direct support of the fissure-eruption hypothesis. The large number of separate sheets of lava, however, demand under the hypothesis mentioned that the earlier overflow should have been broken by fissures, in order to admit of the escape from below of the molten material which rose and overflowed the surface so as to form the later sheets. Dikes should therefore be expected to occur in the lower sheets of lava leading up to the superior layers. Although the Columbia lava has been deeply dissected by stream erosion, only three or four dikes cutting across the layers have been seen. These are situated in the walls of Grande Ronde canyon and are all small, the largest being only about 30 feet thick. Whether these dikes lead to lava sheets higher in the canyon wall and indicate the fissures from which material forming the superior sheets was derived is not certain, for the reason that disintegration has obscured the upward extension of the dikes and made it impossible to trace them for more than a few hundred feet above the present level of Grande Ronde River.

Throughout the hundreds of miles of cliffs formed by the walls of stream channels through the Columbia lava that have come under my notice, with the exception of the locality just mentioned, dikes are absent. There is thus seemingly a weakness in the evidence which should be looked for in support of the fissure-eruption hypothesis,

[1] Bull. U. S. Geol. Survey No. 108, 1893, pp. 67-68.

but this may be removed when the region covered by the Columbia lava, especially in the vicinity of the Cascade Mountains, is more extensively examined.

Extent.—The Columbia lava is by far the most extensive of the geological formations in the far Northwest. It is also the most important from an economic point of view, since by the disintegration and decay of its surface layers it has furnished the wonderfully rich soil on which a large portion of the grain of Washington and adjacent States is raised.

The boundary of this great series of volcanic overflows in eastern Washington, from Snake River northward to Spokane River, and thence westward along the Columbia, has already been briefly described. The Columbia lava occurs also in the Cascade Mountains of Washington and Oregon, and extends southward into California. To the east of the Cascade Mountains it occupies much of Oregon and large portions of southern Idaho. Although its boundaries have not been mapped, it is known to occupy an area of not less than 200,000, and possibly as much as 250,000, square miles.

Thickness.—The Columbia lava, as already stated, was poured out in a molten condition and spread over the country like a series of fiery inundations. The surfaces of the various sheets were originally practically horizontal, but the surface of the inundate country was uneven and, in part at least, mountainous. The depth of the hardened lava at various localities would therefore depend on the character of the topography of the region it covers. The original thickness has been decreased by erosion, but, except in the canyon, this is not great. The loss from the surface of those portions which have not been upraised or tilted is, under the most liberal estimate, not over a few hundred feet.

The maximum thickness of the lava, or, considering it as a congealed sea of molten rock, the deepest sounding, is not known. About the margin of the basaltic flows along the Columbia River, in the "Big Bend country," canyons 300 or 400 feet in depth reveal the granite beneath. Along Snake River Canyon for over 100 miles from its mouth 2,000 feet of lava is in sight. Where Snake River and the Grande Ronde cut into the Blue Mountain uplift, between 4,000 and 5,000 feet of horizontally bedded lava is exposed. This is the deepest section yet discovered, but even there the base of the series is not seen. It seems safe to conclude that the maximum thickness is in excess of 5,000 feet. In the Cascade Mountains, according to Prof. Joseph Le Conte, 3,700 feet of lava is to be seen. From my own observations in that region, however, I should not be surprised if much greater thicknesses are discovered. The average thickness for the Columbia lava in the State of Washington was thought by Lieutenant Symons[1] to be not far from 2,000 feet. In a former report I was dis-

[1] Bull. U. S. Geol. Survey No. 108, 1893, p. 21.

posed to agree with this estimate, but observations since made along Snake River certainly indicate that the average thickness over large areas must be much in excess of the amount stated. Estimates of the average thickness can at present have but little value, however, as even single measurements of the total thickness are lacking, except near the borders of the lava-covered region.

Character of the rock.—The general appearance of the rock forming the widely extended formation under discussion is familiar to everyone in southeastern Washington. It is the common black rock of the country. It underlies all of the wheat lands, and is splendidly exposed in the canyons of the Grande Ronde, Snake, Palouse, and Spokane rivers, and along nearly all of their branches west of the Washington-Idaho boundary. To the geologist this rock is known as basalt.[1] It is dark, usually black, in color, but various tints of gray, green, brown, and red are not uncommon. Most of the variations from the normal black or nearly black color are due to weathering. The upper surfaces of some of the sheets, however, are red, owing to the oxidation of the iron in the rock while it was yet highly heated.

One of the latest lava flows in the great series here considered occurs in Yakima County, between Cowiche and Natches creeks, and differs from all other portions of the Columbia lava now known. The lava sheet referred to consists of what is termed hypersthene-andesite, and contains prominent crystals of the mineral hypersthene.[2] When the Columbia lava is critically studied, it is probable that other rocks nearly related to basalt, but differing from it in chemical and mineralogical composition, will be discovered.

Except when the molten magma cooled with excessive rapidity, as on coming in contact with water, or flowed over wet sands and clays, the material composing it became crystallized. The slower the cooling, the larger the crystals that were formed. The central portions of the various sheets are for this reason usually coarser in texture than their surfaces. In a few instances the bottom of a layer is almost glassy for an inch or two in thickness, owing to sudden cooling. Fragmental material, sometimes found in sheets between the layers, and probably formed by the disintegration of the highly heated rock on coming in contact with water, is also excessively fine grained and vitreous in luster.

The crystals of which the basalt is composed can seldom be seen by the unaided eye, but when thin sections of the rock are studied with

[1] A characteristic sample of this rock from Mill Creek, near Walla Walla, has been examined by Mr. J. S. Diller, who reports as follows concerning it: "The rock is a characteristic basalt, composed of plagioclase feldspar, augite, olivine, and magnetite, with considerable globulitic base. The feldspars are well developed, with crystallographic boundaries. The augite is less well developed and is generally granular, as is also the olivine. The magnetite is mostly in octahedral crystals, which for the most part are arranged in groups made up of lines perpendicular to one another. The rock is perfectly fresh and unaltered."

[2] Bull. U. S. Geol. Survey No. 108, 1893, pp. 64-65.

the assistance of a microscope their nature is clearly shown. The minerals which make up the bulk of the rock are feldspar, augite, olivine, and magnetite, and crystals of other minerals are scattered thickly through uncrystallized portions of the magma, which forms a glassy groundmass. The minerals mentioned are silicates of alumina, magnesia, soda, potash, lime, iron, etc., and when the rock decomposes on weathering these substances are more or less perfectly liberated.

Chemical analyses of basalt show that in general it contains from 46 to 57 per cent of silica and from 11 to 22 per cent of alumina, together with lime, magnesia, potash, etc., in proportions varying from a small fraction of 1 per cent to over 10 per cent. It is the presence of lime, potash, and phosphoric acid in the basalt that gives the soils formed from its decay much of their richness for agricultural purposes.

Columnar structure.—The columnar structure of many of the lava sheets gives interesting details to the massive architecture of the canyon walls at many localities. This structure, as is well known, is due to the shrinking of the rocks on cooling. The columns have their longer axes at right angles to the cooling surfaces, and consequently, in horizontal sheets, are vertical. When a canyon is cut through a series of beds having this columnar structure, the section of each layer presents the appearance of a long colonnade of closely set vertical shafts.

The columns are most commonly hexagonal in cross section, although other forms, with sides ranging from three to eight, may be found They are frequently 3 or 4 feet in diameter, but sometimes larger, and from a few feet to 30 feet or more in height. The larger columns are not usually sharply defined, as their sides are apt to be irregular. The most perfect examples have usually a diameter of from 15 to 25 inches. One of the best displays of columnar structure that I have seen occurs on the left bank of Snake River, about 3 miles above the mouth of Alpowa Creek. A long colonnade is there exposed, forming a vertical wall 30 to 40 feet high, in which the shafts are remarkably even and of uniform size. The columns are mostly six-sided and about 14 inches in diameter. Beneath this columnar layer is a bed of pure-white volcanic dust. The removal of this soft layer by the river has led to the undermining of the heavy sheet of basalt resting on it and the breaking away of the jointed rock, so as to form the wall in which the columnar structure is so well displayed.

The breaking of the basalt into columns is due, as stated above, to shrinkage on cooling. Breaks in the rock, termed joints, are thus formed. These are best developed when cooling is slow, and for this reason the central portions of lava sheets are frequently regularly jointed—that is, divided into well-defined columns—while the top and bottom portions of the sheets are confusedly jointed, and sepa-

rate into blocks of all shapes and many sizes. The irregularly jointed rock does not fall apart so readily as that in which the joints are parallel and well developed. It is for this reason that the rows of columns exposed in the canyon walls so frequently rise from a projecting base and support an overhanging cornice above.

In some localities, particularly where the basaltic columns are of large size, their surfaces present a network of grooves looking like the cracks formed in the surface of mud on drying. The origin of these peculiar markings was not apparent until weathered surfaces were examined. It was then found that the columns frequently have a well-defined internal structure. They are formed of small columns similar in form to the main shafts, but usually only an inch or two in diameter. These secondary columns radiate from a confusedly jointed central core and terminate in more or less regularly shaped prisms at the surface of the main column. It is the junction of the bounding planes of the secondary columns with the surface of the main shafts that gives rise to the peculiar figures mentioned above. These figures, frequently six-sided, but usually irregular, are best seen when the surfaces of the main columns are somewhat weathered. The cracks or planes of jointing that define the sides of the large columns are, as already stated, at right angles to the cooling surfaces. The secondary columns are at right angles to the master joints, which determined the cooling surfaces of the material forming the columns bounded by them.

The best locality for studying this secondary columnar structure that I have noticed is on the left bank of Snake River, about 6 miles above Asotin, where an excavation for a road has recently been made at the base of a great precipice.

The sides of the columns into which the Columbia lava has so frequently been broken seldom present plane surfaces, but are irregular in many ways. The convexities on the side of one column fit accurately into depressions in the sides of the adjacent columns and serve to lock the columns together, and thus admit of their standing in vertical precipices. The columns in the face of a cliff are frequently so loose that one can move them with the hand, but the interlocking of their irregular sides with their neighbors holds them in place.

The series of vertical joints which divide the horizontal sheets of basalt into columns are frequently crossed by other joints or breaks, which are horizontal. There are at least two classes of these horizontal joints, one of which affects individual columns, while the other runs through a large series of columns.

The cross joints which affect individual columns break them into sections from a few inches to perhaps 3 or 4 feet in length. The summit of each section is commonly concave, or depressed, so as to form a saucer-shaped hollow, into which fit the rounded ends of the sections next above. It is seldom, however, that this ball-and-socket

arrangement, so well displayed at the Giant's Causeway, Ireland, on the Isle of Staffa, Scotland, and in other classical exposures of basaltic rock, is characteristically exhibited in the Columbia lava.

The other variety of horizontal jointing, of which mention was made above, extends for long distances, and frequently affects a series of vertical columns several miles in length. These breaks make important division planes in the canyon walls. While in general horizontal, they sometimes make sharp downward bends, but when this occurs the columns still maintain a direction at right angles to the breaks—that is, the joints are parallel with the cooling surfaces that controlled the arrangement of the columns. When the horizontal division planes make a sharp downward curve, the columns radiate from a center situated above. When two or more generally horizontal division planes have been developed, they are strictly parallel with each other and have similar downward curves where groups of radiated columns occur. The vertical distance between two well-defined planes is in some instances not over 3 or 4 feet; at other times the interval is 20 or 30 feet.

The widely extended horizontal joints just described may be distinguished from bedding planes by the fact that the generally vertical columns cross them without change in direction, and also by the fact that they are narrow and sharply defined; and again, for the reason that the rocks above and below are not scoriaceous and have none of the features that characterize the surface and basal portions of lava flows.

So far as I am aware, these widely extended horizontal joints have never been explained, but their parallelism with the surfaces of the lava sheets suggest that they are due to the shrinking of the rock as cooling progressed from the surface downward.

While the systems of vertical columns and frequent presence of horizontal joint planes make the regular jointing conspicuous, the fact is not to be overlooked that the rock, where this systematic arrangement is not pronounced, is also broken in a similar way, but without regularity. This becomes especially evident when apparently solid cliffs crumble on weathering, and an irregular series of joints is developed.

Scoriaceous surfaces and amygdaloids.—The surfaces of the various flows of Columbia lava are usually cellular or scoriaceous, while at a depth usually of a few feet the rock is compact and practically without cavities. As is well known from the study of modern lava streams, the oval holes and blebs, sometimes drawn out by the flow of the still plastic rock so as to be greatly elongated, are due to the expansion of steam and gases within the highly heated and still pasty material. On account of the action of the oxygen of the air on these rocks while still heated, or afterwards as they cooled and weathered, the iron contained in them was usually oxidized and the rocks acquired a red color. The scoriaceous layers are therefore frequently red.

The upper surfaces of the various sheets are characterized especially by a cellular or scoriaceous condition; the under surfaces also have the same characteristics, although usually not so well marked. As a lava stream advances, its surface becomes cooled and forms a scoriaceous crust, which may be sustained for a time on the still moving and highly liquid lava beneath. A hardened crust also forms on the extremity of the moving sheet, and is rolled under as the sheet advances. Scoriaceous rock is thus transferred from the surface to the base of a lava stream. Where sheet has succeeded sheet, each formed by an outpouring of molten rock, it is frequently difficult to say just where the junction plane separating them is located, for the reason that the rough, scoriaceous surface of the lower sheet is involved and embedded in similar material, which was poured out over it.

The basal portions of lava sheets, especially when they rest upon soft deposits like clay, are sometimes smooth, and have a dense outer rind with a glassy structure, due to rapid cooling. An instance of this nature observed at Spokane is described on page 53.

The cavities in scoriaceous lava frequently become filled with mineral matter, and on breaking open the rock that has undergone this change kernel-like grains are found instead of cavities. The mineral matter in such instances, most frequently some form of quartz, has been deposited from solution by percolating water since the rock hardened. Rocks containing cavities which have been filled in this way are termed *amygdaloids*, from the resemblance of the kernels to almonds. The kernels or amygdules may be of any shape, however, and not infrequently in the Columbia lava are very irregular. In some of the layers of the lava, as was observed especially in the canyon of the Grande Ronde, the cavities are not completely filled, but each one has a thin lining of quartz. As the rocks weather the small hollow kernels are liberated and occur scattered through the soil.

Larger cavities in the lava at times become filled with a form of silica known as chalcedony, which has a yellow color and looks like bright yellow resin. When this mineral presents bands or layers of different color, it is known as onyx. The presence of this mineral in the Columbia lava has led to crude mining at a few localities with the hope of discovering beds of onyx, but thus far little if any material of commercial value has been found.

Another form of silica, known as opal, also occurs as amygdules in the Columbia lava, and very beautiful stones having bright colors have been obtained. These stones are of the variety known as harlequin opals, and are frequently of great brilliancy and in every way of excellent quality. Opal mining has been carried on in a small way at Moscow and a few other localities in Idaho, and the conditions seem favorable for continuing this industry. Common opal, of a milky-white color and without the gorgeous play of colors that makes the harlequin opal one of the most beautiful of gems, occurs at very many horizons, and so long as we do not know the precise conditions that

cause the variations in the character of the silica deposited in cavities in the lava, one may hope to find the variety having brilliant colors at almost any locality.

Extent and thickness of individual sheets.—In the walls of many of the canyons that have been excavated in the balsatic plateau, and especially in Snake River Canyon and along Spokane and Columbia rivers, individual layers of lava may be traced for miles, and even for scores of miles, without notable variation in thickness or in general characteristics. I have not made continuous journeys of more than 25 or 30 miles through the canyons, but have entered them at various places. Localities on their brinks frequently command a view of 10 or 15 miles of the opposite wall, and from exceptionally favorable localities for observation, like the summit of Mount Wilson, the edges of the lava sheets may be seen clearly exposed for not less than 40 miles. In no instance have I seen a lava sheet thin out or in fact present any marked variations. It is evident that the lava was highly fluid at the time of its extrusion, and that it spread widely over the country in horizontal sheets of remarkably uniform thickness. Few exact measures of the thickness of individual sheets have been made, but by eye estimates it is safe to say that many sheets are from 40 to 60 feet thick, and not infrequently layers of more than double these amounts occur. The average thickness, I should judge, would be 60 or 80 feet.

Number of overflows.—In almost any view of the walls of Snake River Canyon, which furnishes the best section known of the Columbia, 50 or 60 well-defined bands may be seen, which at first sight appear to be the edges of individual lava sheets. A closer examination will show, however, that some of even the most conspicuous horizontal partings do not mark the junction of separate lava sheets, but are due to the horizontal jointing already described. Some of the bands, too, are due to the columnar structure of the central portion of the various sheets adjacent to other portions of the same flows which are confusedly jointed. For these reasons, and also because the terraces or steps in the canyon walls are covered with loose rocks and soil, banked high against the cliffs above, it is difficult to determine how many individual lava sheets have been cut through in order to form the canyon. Reliable evidence of the vertical extent of the individual sheets of lava is sometimes furnished by interbedded layers of sedimentary origin, like sand and clay, and also by sheets of fragmental material, termed lapilli and volcanic dust. It is infrequent, however, in eastern Washington that evidence of this nature can be had. Usually, the only safe method of distinguishing the individual flow is by noting the occurrence of scoriaceous bands.

On counting the numbers of scoriaceous bands exposed in the walls of Snake River Canyon, I found that at least eight lava sheets had been cut through to form the canyon where it is 3,000 feet deep. I am by

no means confident, however, that this is the total number of sheets in sight. Although the canyon walls appear to offer abundant facilities for learning the number of individual flows exposed in them, yet difficulties arise when one attempts to measure an actual section, for the reason that large portions of the cliffs are concealed by talus slopes. I must confess that I did not make such a detailed study of the canyon walls as I had hoped to do, for the reason, in part, that I delayed the task until the most favorable locality should be found. The best localities for such a detailed study are in Snake River Canyon, above Asotin, but when in that section my time was too limited to do all the work I desired to accomplish.

Geological age.—Beneath the Columbia lava in Kittitas County there are coal-bearing rocks, termed the Kittitas system, which, as shown by their abundant plant remains, are probably of Eocene age, the oldest of the principal divisions of the Tertiary. Resting on the lavas in the same general region, and in part interbedded with them, is another series of beds which have been referred to the Miocene, or the middle portion of the Tertiary. This evidence seems conclusive that the Columbia lava was poured out somewhere near the middle of the Tertiary period.

Road material.—The basalt will probably never be in demand for architectural purposes, for the reason that it is too hard to be smoothed or polished economically, and also because of its dark color. It is of value, however, for rough masonry, as, for example, the foundations of buildings, abutments of bridges, etc. When crushed, it furnishes a most excellent material for macadamizing roads and streets or ballasting railroad tracks.

The fine soil of central and eastern Washington makes poor roads, as it wears easily, rises in dust when dry, and is soft and slippery when wet. At present the country roads and even the streets in the towns have but little attention given to them. But as the State grows in wealth and culture better roads will be demanded. The basalt will then furnish a limitless supply of material for their improvement.[1]

Artesian wells.—The artesian wells at Pullman, Palouse, and other places in Whitman County and adjacent portions of Idaho have been drilled in the Columbia lava. If other similar wells are to be had in southeastern Washington, they will have to penetrate the same series

[1] In Walla Walla and some other towns the practice prevails of covering the dusty streets to a depth of 5 or 6 inches with wheat straw. This temporary expedient is an improvement, but should not be allowed to delay the making of solid and practically dustless roadbeds with broken stone, on the macadam plan.

The country roads throughout southeastern Washington are frequently impassable for loaded wagons during wet weather, and, besides, follow section lines, without reference to hills or valleys. Economy, if no higher principle, demands that the rectangular road system should be abandoned in many regions and an effort made to give the roads gentle grades and smooth, hard surfaces.

The improvement of country roads, especially by the macadam process, is discussed by Prof. N. S. Shaler in the Sixteenth Annual Report of the United States Geological Survey.

of lava flows. In dealing with the artesian problem it is necessary to consider various conditions besides the character of the lava, and this discussion will therefore be postponed to a later portion of this report.

CLAY AND GRAVEL INTERSTRATIFIED WITH THE COLUMBIA LAVA.

Yakima Valley.—In the region occupied by the Columbia lava in central Washington, to the west of Columbia River, and described in a previous report,[1] there are several widely spread sheets of clay, gravel, sand, etc., of sedimentary origin, interleaved with the lava sheets. The brief account given in the report referred to, of the relation of the lava to these interbedded deposits, is as follows:

> Near the upper surface of the Columbia lava, in the Yakima region, there is a thin layer of clay formed as a sediment in a Tertiary lake, and subsequently covered by a lava flow a hundred feet thick. Above this bed of basalt and resting evenly on its surface are gravels and fine, evenly bedded lacustral sediments, having a thickness of 125 feet; then comes an interstratified sheet of columnar basalt, from 40 to 100 feet thick, which may be traced from the hills about Ellensburg eastward to Columbia River and which appears again in the eastern portion of Saddle Mountain. Above this layer there are other lacustral deposits, belonging to the John Day system. Besides the widely spread interstratified sheets of basalt there are others more local and less well known; one of these was penetrated while drilling the artesian wells in Moxee Valley.

Southeastern Washington.—The examination made of the geology of southeastern Washington failed to show that deposits of aqueous origin, interstratified with the Columbia lava, are there as numerous as in the region mentioned above, to the west of the Columbia. This is an important matter, as it has a direct bearing on the question of artesian water supply. The localities where sedimentary beds occur interleaved with the basalt to the east of the Columbia are mostly near the eastern boundary of the basaltic plateau, in Spokane, Whitman, and Asotin counties.

A possible reason for the fact that a greater number of sedimentary beds interstratified with the basalt have been recognized in the region west of the Columbia than in the country having a similar geological history to the east of that river may be that in the western area the lavas and interbedded deposits have been disturbed from their original horizontal position and the vast blocks bounded by faults have been upraised so as to expose the edges of the strata composing them and to allow the weathering out of the soft beds, in part, in such a manner as to reveal their presence in the topography. In southeastern Washington the rocks are, for the most part, still horizontal, and the only sections exposed to view are in canyon walls. Unless the escarpments are unusually steep, the soft beds are apt to be concealed by talus slopes and soil, and their presence masked. A more detailed study of

[1] Bull. U. S. Geol. Survey No. 108, 1893, p. 22.

the geology of this region will perhaps reveal a greater number of sedimentary beds in the basaltic area than is at present known.

Walla Walla Valley.—At a locality on the south side of Walla Walla Valley, about midway between Walla Walla and Wallula, the upper portion of a bed of fine clay beneath basalt is open to view for a short distance. The thickness of this bed that is exposed to view is only about 4 feet, but its total thickness is unknown.

Asotin country.—Near Asotin, on each side of Asotin Creek and less clearly exposed in the neighboring portion of Snake River Canyon, there are two horizons, one about 360 and the other approximately 700 feet above the town of Asotin, at which light-colored, evenly stratified clays appear between thick layers of basalt. The lower bed of clay is in the neighborhood of 40 feet thick; the upper one is certainly much thicker, but has not been measured. These sheets of clay are probably of wide extent, but owing to the manner in which comparatively thin, soft layers in a great series of hard beds became concealed at their outcrops in canyon walls by débris and soil, their presence was not clearly recognized in the bluffs and precipices bordering Snake River.

Palouse country.—At Pullman the upper portion of a bed of heavy clay is exposed near the bottom of the steep-sided valley in which the business portion of the town is located. This bed, as shown in railroad cuts northwest from the town, and in part by well borings, is about 30 feet thick. Its upper portion, to the depth of from 4 to 6 feet, has been baked and hardened by the heat of the lava that flowed over it, and is frequently dark, almost black, in color. At the immediate junction the clay is so much altered that it is difficult in small exposures to distinguish it from the overlying basalt, especially when the latter is somewhat weathered and disintegrated. Numerous vertical joints in the altered clay also increase its resemblance to igneous rock. This hardened surface portion of the stratum of clay, when traced downward, changes to unaltered clay, which in some places is yellow, light colored, and sandy. The thickness of basalt above this stratum is not less than 150 or 200 feet.

About 60 feet below the clay layer just described there is a second bed of sedimentary origin, composed of light-colored, unconsolidated quartz-sand and gravel, containing an abundance of mica. The rock intervening between these two sedimentary layers is compact, black basalt. The stratum of sand and gravel referred to has been revealed in drilling artesian wells, and has been penetrated to the depth of a few feet, but its thickness is unknown. It is abundantly water bearing.

The upper sedimentary bed at Pullman is plainly the sediment of a lake that existed on the basaltic plateau during an interval between the outpourings of lava. The layer of gravel and sand, 60 feet below, is of the nature of a stream deposit, or possibly the shore formation

of a lake, and was derived mainly from the disintegration of the granitic hills bordering the basaltic plateau on the east. The distance from Pullman to the nearest granitic hills to the eastward that rise above the present surface of the plateau is only about 8 miles.

In drilling a well at Palouse, 12 miles northeast of Pullman, a water-bearing stratum of sand and gravel similar to that beneath Pullman was reached at a depth of about 100 feet below the surface. Palouse is, by aneroid measurements, 100 feet higher than Pullman, hence the water-bearing beds at these two localities are not the same. The gravels and sands at a depth of 100 feet at Palouse may represent the clay layers exposed in the streets of Pullman.

At Garfield a drilled well was put down to a depth of about 300 feet, but so far as I can learn no sedimentary deposits were reached. Three miles northeast of Garfield, however, on the farm of James Walters, a drilled well, 113 feet deep, passed through basalt for 65 feet from the surface and entered clay 14 to 15 feet deep, beneath which water-bearing sand was reached, from which water rose and overflowed at the surface.

In a north-and-south belt of country in general, some 8 or 10 miles wide, beginning about 4 miles south of Pullman and extending to beyond Rosalia, there are reported to be 40 or 50 wells that penetrate water-bearing strata interbedded with the sheets of basalt. The records of these wells are not all available, and in general the level of the ground at the surface where they are located is not accurately known. For these reasons it is impracticable at this time to construct a section of the rocks of the region.

A mile south of Palouse, and again about a mile west of Garfield, deposits of sandy clay and of pure white kaolin have been opened. At the first-mentioned locality the clays are used for making fire brick and pottery. These deposits are evenly stratified and evidently of lacustral origin, but the depth of soil about them renders it uncertain whether or not they are interbedded with basalt. There is little doubt, however, that they represent lake deposits that were covered with basaltic overflows, and that they were revealed at a later period by the erosion of stream channels. These deposits are similar to certain clays in Spokane, described later, that are covered with thick sheets of basalt; a fact which lends support to the hypothesis just stated.

The conditions described in a general way as existing from Pullman northward to Rosalia are probably continued northward to Spokane, but this tract of country was not examined. At Spokane I spent two days in making a hasty study of the exceedingly interesting geological features there well displayed.

Spokane.—Excavations made in the southern part of the city of Spokane have revealed important beds of coarse gravel and sandy clay with a thick sheet of Columbia lava above. Similar beds of basalt occur beneath the sedimentary layer, as is shown by other excava-

tions, as well as along the adjacent portions of Spokane River. The most instructive of the excavations referred to is near the south end of Barnard street, now graded, where an electric-car line leaves the street and curves abruptly eastward. This cut is in general about 20 feet deep and approximately 150 feet long. For about 130 feet from Barnard street thin-bedded sandy clays with much mica and containing fossil leaves are exposed. A thickness of 10 or 12 feet of this deposit is in sight, but its bottom is nowhere revealed.

Resting in an irregular manner on the micaceous clays are coarse, uncemented gravels and water-worn bowlders. Above the gravel lies the covering of basalt, which, as shown in neighboring cliffs, is not less than 50 or 75 feet thick. An interesting feature of the basal portion of the covering sheet of basalt is the irregularity of its lower surface. The bottom of the basaltic sheet has rounded, smooth-surfaced protuberances or corrugations, between which the gravel and bowlders, together with detached fragments of the micaceous clay, frequently 12 to 16 inches in diameter, extend upward for 8 or 10 feet. Fragments of the micaceous clay in contact with the basalt show evidences, in their compactness and reddish color, of the effect of the heat of the lava which came in contact with them.

A rough sketch of the exposure described above, as seen in the north wall of the cut, is here reproduced from my note-book:

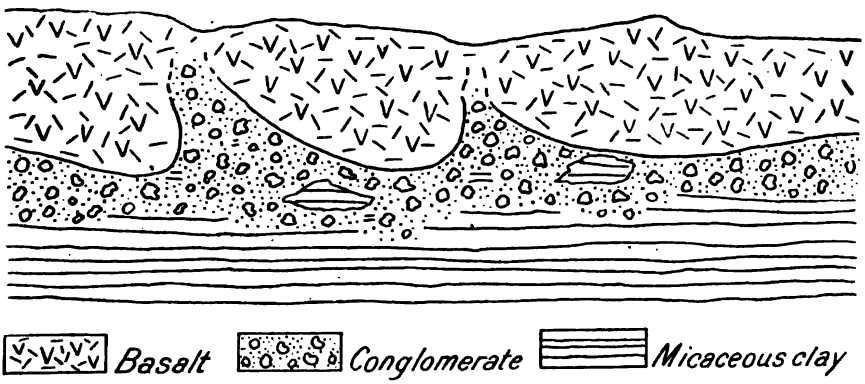


FIG. 1.—Section of lava flow and lake beds at Spokane.

The surface of the basalt is not only smooth, but when broken was found to be exceedingly dense and hard. The rock to a depth of about 2 inches has a vitreous luster and is almost a glass. Evidently this surface layer was cooled quickly.

The explanation of the peculiar relation of the basalt to the gravel and clays beneath it seems to be that the lava in a molten condition flowed over the deposits on which it rests in a direction from left to right, as shown in the above section. The loose deposits were disturbed and forced along in front of the flowing lava until the resistance became sufficient to check its progress, and at the same time the lava

became cool and rigid. Still liquid lava broke out from the face of the arrested flow and advanced beyond the previously cooled border, overflowed the accumulation of stones and fragments of the micaceous clay, and again forced up a ridge of the loose material. This process was repeated several times in the portion of the flow exposed, and accounts for the marked inequalities in the under surface of the basaltic sheet and the manner in which confused masses of gravel and detached fragments of clay extend upward into the basalt.

The explanation just suggested is in harmony with the manner in which lava flows are known to advance. In describing the flow of lava streams on the Island of Hawaii, Dutton says:[1]

> After running some miles it [the molten lava] reaches more level ground, where it spreads out in great lakes or fields. It also cools on the surface, which gradually freezes over. But it is still hot within, and beneath its hardened covering the liquid rivers are still running, and at the edges and along the front of the great sheet the liquid lava constantly breaks forth, pushing out fiery rivulets in advance and laterally.

The lava that covers the lake beds and gravel deposit in Spokane appears to have advanced into a shallow lake, the bottom of which was disturbed and forced up in ridges. The contact of the lava with the water caused it to congeal rapidly and to form a glassy outer layer.

Near Spokane there are deposits of kaolin, similar to that already mentioned as occurring near Palouse, but remarkably fine and pure. I have not visited the pits from which this material is obtained, but from its character it appears to belong to the series of deposits under consideration.

Deposits of volcanic dust and lapilli.—On a previous page mention has been made of a layer of pure-white volcanic dust beneath a thick sheet of columnar basalt in Snake River Canyon, above the mouth of Alpowa Creek. This deposit owes its origin to a violent volcanic eruption, the location of which is unknown, that blew great quantities of exceedingly fine dust high in the air. The dust was carried by the wind to great distances and spread as a sheet over the land. This eruption occurred during one of the later intervals in the outpouring of the Columbia lava and the deposit was buried by the next succeeding lava overflow. The stratigraphic relation of this bed of volcanic dust to the overflow of Columbia lava is similar to that of the interbedded lacustral clays and stream-deposited sand.

In excavating for an irrigating canal on the side of Snake River Canyon at Pigeon Rock, below Asotin, a bed of coarse, yellowish, fragmental volcanic material over 10 feet in thickness was exposed. This deposit has compact lava sheets above and below, and owes its origin to the deposition of fragments of volcanic rock, frequently 2

[1] C. E. Dutton, The Hawaiian Islands and People; a lecture delivered at the United States National Museum, 1884, p. 13.

inches in diameter, which were blown out by a volcano, or perhaps formed by molten lava coming in contact with water. The fragments composing this lapilli sheet are of the same character as the dense, vitreous layers already described as forming the under surface of a lava sheet at Spokane. These lapilli deposits, unlike the sheet of white volcanic dust mentioned above, belong to the eruptions that poured out the Columbia lava, and are not, therefore, of distant origin.

Résumé.—Interleaved with the sheets of basalt forming the series named the Columbia lava, there are, as just shown, sheets of lacustral clay and of stream-borne gravel and sand, and layers of volcanic dust and of volcanic fragments termed lapilli. The lake beds appear to occur mostly near the border of the lava-covered country, for the reason that, in eastern Washington at least, the lava sheets flowed toward the mountains, and on congealing dammed their draining streams. The surface of the cooled and hardened lava flows must have had a slight slope in the direction of flow. The supposed absence of lake beds over the more central portions of the lava may be due to a lack of information, but seems to be a necessary result of the manner in which the lava sheets encroached on the mountains and blocked their draining streams. Shallow lakes were probably formed on the surfaces of the cooled lava sheets far from the mountains, but being at a distance from highlands that could furnish débris, they would not be deeply filled, and records of their existence would not be conspicuous.

The layers of volcanic dust, from the nature of their origin, should be widely spread, but up to the present time they have been observed at but few localities. Sheets of lapilli have been noted in the Big Bend country and near Asotin, but whether they are extensive or not remains to be determined. These various deposits found between the layers of Columbia lava at different horizons not only record interesting episodes in the history of the basaltic inundations, but, as will be shown later, have a direct and important bearing on the question of artesian water supply.

JOHN DAY SYSTEM.

In my report of a reconnoissance in central Washington, already cited, certain lacustral deposits are described which rest on the surface of the latest extensive lava flow of the Columbia system. This series of lake sediments consists principally of stratified clays, with thick strata of white volcanic dust, and in certain localities contains beds of coarse conglomerate. It is termed the John Day system, for the reason that it is thought to be an extension of a similar formation which occurs in John Day Valley, Oregon. The connection between these two areas has not been actually traced, however, and the correlation just suggested must be considered as provisional.

Beds of light-colored clay and of white volcanic dust, which have been referred to the John Day system, occur at the White Bluffs

of the Columbia, 30 miles above Pasco, and are also well exposed in Naches Valley and near Ellensburg, in Yakima County. At these localities the impressions of the leaves of a large variety of plants and the bones of extinct animals have been obtained. The plant remains indicate that the shores of the ancient lake into which they were blown or washed by tributary streams were clothed in a varied and beautiful flora, resembling, in a general way at least, the vegetation of the South Atlantic and Gulf States at the present day. In the ancient forest and about the shores of the old lake, now known as Lake John Day, a veritable menagerie of strange and in part gigantic beasts found a congenial home.

From the White Bluffs of the Columbia southward to the region described in this report there are no barriers, but the surface of the country rises gradually from the broad valley of the Columbia to the basaltic plateau of northeastern Washington. From studies made along the Columbia in 1892, I was led to the conclusion that Lake John Day extended far eastward and covered nearly all of southeastern Washington, even to the base of the Blue Mountains. This view is now known to have been in part erroneous. The sediments of Lake John Day are but poorly exposed to the east of Pasco and Wallula, and their extent in that direction, although not clearly shown, is certainly far short of the Blue Mountains and of the Idaho boundary. They cover the Eureka flats, however, as is shown by a well 198 feet deep at Eureka Junction, which is all in strata similar to those exposed in the White Bluffs of the Columbia, but does not reach the bottom of the formation. Fossil leaves were found in the rock removed in digging the well similar to those obtained from other portions of the John Day system. With the exception of the rocks found at Eureka Junction, no exposures of the Lake John Day system have been recognized in the region treated in this report. The sediment of the old lake does not occur above the Columbia lava in the vicinity of Walla Walla, Dayton, and Starbuck, and its eastern shore must have been to the west of these localities.

The lacustral deposits described in the preceding section as being interbedded with the Columbia lava are of about the same age as the John Day system and were accumulated under similar conditions. They should perhaps be included in the same system, but further study is necessary before a conclusion in this connection can be reached.

RIVER TERRACES.

In describing the canyons of Snake, Spokane, and other rivers in a preceding section mention was made of gravel terraces which occur in them. Little remains to be said in reference to these terraces, except to indicate their place in the geological history of the region where they occur. That they are younger than the Columbia lava and the lake beds, either interleaved with them or resting on their

surface, is shown by the fact that they occur in canyons that have been excavated in these formations. The canyon of Snake River, for example, was cut to its present depth before the gravels forming the great banks which occur at certain localities within it were deposited. The canyon was filled in with gravel from side to side to the depth of 360 feet and then reexcavated. Since the river cut through this gravel deposit, removing by far the greater portion of it, but little if any progress has been made in deepening its bed in the solid rock below. Evidently the gravel deposit belongs to a comparatively modern episode in the history of the great gorge. Several considerations lead to the conclusion that the canyon was excavated to its present depth in late Tertiary times, and was filled in with gravel during the Glacial period. If this inference is correct, the amount of excavation done since the Glacial period is trifling in comparison with the work performed by the river previous to that period.

SOILS.

ORIGIN OF SOILS.

Soils in general consist of more or less thoroughly disintegrated and decomposed rock. The surface layer usually contains organic matter termed humus, derived from the partial decay or chemical alteration of organic matter, principally of vegetable origin.

In many regions the breaking down of the rock supplies more material for soil making than is removed by streams or blown away by the wind. Again, denudation may keep pace with disintegration and decay and all of the loosened soil material be removed, so as to leave bare rock surfaces. Much of the soil material removed from one area is redeposited in another area, and hence it is convenient to recognize two kinds of soils, classified in reference to whether they have been removed from their place of origin or not. These two general classes are *residual soils* and *transported soils*. Under each of these divisions many minor subdivisions, dependent on chemical or mechanical composition, have been recognized.

The residual soils are such as originate from the disintegration and decay of the rocks on which they rest. They are the residue left after a long process of weathering and leaching by percolating water, which has removed most of the more easily soluble constituents. Some movements in the soil cap probably always attend this change, but the residue remains practically on the area where it was formed. In recognition of this fact the term "sedentary soil" is sometimes used instead of the one here employed.

The transported soils consist of the products of rock disintegration and decay and of rock abrasion, which have been removed from the area where they were produced, usually through the agencies of streams, glaciers, or the winds, and redeposited. A familiar example

of soils of this class is furnished by the silts, sands, and clays forming the flood plains of streams.

In the region represented on the accompanying map not only are both transported and residual soils abundantly represented, but several varieties of each, dependent on mechanical and chemical differences, may be easily recognized.

SOILS OF THE VALLEYS AND CANYONS.

The soils in the valley bottoms in southeastern Washington, more especially in the smaller valleys and along the borders of the smaller streams, although belonging strictly to the transported soils, are frequently of the same character as the soils of the adjacent uplands, or plateau surface, and have been removed but short distances from their place of origin.

The bottom lands adjacent to Walla Walla River and the sand bars in Snake River Canyon, in the valley of Spokane River and elsewhere, are typical examples of transported soil. The mineral and rock fragments composing these soils are, in general, more varied in character than the grains in the residual soils, and have been brought to the localities where we now find them by stream transportation.

About Wallula and Pasco the country is covered over large areas with sand and dust. The surface coverings of this desert-like region represent another variety of transported soils, in which wind is the transporting agency.

The transported soils in the region under discussion may be easily recognized, particularly on account of their topographic relations and the heterogeneity of the rock fragments contained in them, and need not be considered further at this time.

SOIL OF THE WHEAT LANDS.

The deep, rich soil covering the broad basaltic plateau of southeastern Washington and extending widely into Oregon and southwestern Idaho is a residual soil formed by the disintegration and decay of the lava rocks on which it rests. This is the justly celebrated soil of the wheat lands.

To the residual material left by the breaking down and partial solution of the lava have been added minor quantities of terrestrial and volcanic matter; and cosmic dust, or the particles derived from meteors which come to the earth from space, should also be mentioned in this connection.

The plateau is covered nearly everywhere with a rich soil that is unusually fine and porous and free from stones and obstructions of every kind. To the plow it offers scarcely more resistance than so much meal. The surfaces of plowed fields are of a dark-brown, almost black color, due to organic matter or humus. This humus is in part an inheritance from the centuries during which the rolling

WHEAT LANDS NEAR MOSCOW, IDAHO.

uplands were covered with bunch grass, and in part has been derived from the decay of the stubble of wheat fields. At a depth usually of 5 to 8 feet below the surface the dark color fades away and the subsoil, equally fine and homogeneous, and having the same mineral composition, but of a light and usually a yellowish color, is revealed. The subsoil varies in depth with the relief of the surface and with the topography of the underlying hard-rock surface, but is nearly always deep. Systematic measurements are wanting, but judging from the thickness of superficial material revealed in wells, railroad cuts, and other excavations, the subsoil has an average depth of between 50 and 80 feet. Many natural and artificial sections that were examined revealed a depth of 40 to 50 feet, usually without exposing the underlying rock.

In all sections of the subsoil it appears as a fine, homogeneous, unstratified formation, having a uniform light-yellow color.[1] There are frequently indications of vertical joints, or narrow dividing planes, but whether these have developed in the soil, or are possibly an inheritance from the basalt from which it was derived, is an open question. Traversing the subsoil from top to bottom are innumerable minute and almost capillary tubes. These are, in a general way, vertical, but they are curved and otherwise irregular. A single tube can seldom be traced for more than 3 or 4 inches, and their extremities are seldom discoverable, but scarcely a cubic inch of the subsoil is without a number of them. In the humus layer, however, they are absent.

Geologists will, I think, at once recognize, from the above description, the close similarity of this deep subsoil to loess deposits. This resemblance includes the color, the dust-like fineness of the material, the absence of stratification, and the presence of minute and nearly

[1] A characteristic sample of the soil of the wheat lands has been submitted to a mechanical analysis made by Milton Whitney, chief of the division of soils in the United States Department of Agriculture, with the following results:

Mechanical analysis of soil from near Pullman, Washington.

Diameter (in millimeters).	Conventional name.	Per ct.
2 to 1	Fine gravel	0.00
1 to .5	Coarse sand	0.04
.5 to .25	Medium sand	0.16
.25 to .1	Fine sand	1.31
.1 to .05	Very fine sand	53.72
.05 to .01	Silt	26.29
.01 to .005	Fine silt	2.97
.005 to .0001	Clay	8.58
Total mineral matter		93.07
Loss at 110° C		2.45
Loss on ignition		5.20
Total		100.72

vertical tubes. These features also characterize the adobe deposits of arid regions.[1]

The close similarity between the soils of the basaltic plateau and the loess of China, which is supposed by many to consist of wind-deposited dust, has led some careful observers to conclude that the soil of eastern Washington is really a deposit of dust that has been drifted from a distance by the prevailing winds. The minute tubes referred to are considered under this explanation to be due to the rootlets or stems of grasses about which the dust was deposited, the plants continuing to grow as the dust accumulated. There are several objections to this hypothesis, however, as will be shown below.

In numerous sections the surface of the basalt beneath the subsoil has been examined and always found to be deeply decayed. A gradual change can be traced from hard, black basalt, which reveals no signs of weathering, upward through yellow and partially disintegrated portions of the same layer, to rock fragments that are soft and much decayed, and from this, again, to fine soil containing recognizable rock fragments, and finally to the exceedingly fine porous subsoil. Scores of localities where this gradual change is exhibited have been examined, and the number might easily be increased to hundreds.

Chemical analyses of a large number of soils from various localities in Washington and Idaho, including samples from the basaltic plateau, have been made by the chemists of the agricultural experiment stations at Pullman and Moscow.[2] These analyses show that the chemical composition of the soil on the basaltic plateau is such as might be expected to result from the weathering of the solid rocks beneath.

The disintegration of rocks is usually accomplished in part by changes of temperature and by the expansion of water held in crevices and absorbed by pores and capillary passages, on freezing, and in part by the solvent action of percolating waters and, as recently determined by G. P. Merrill, the expansion of minerals in changing to a hydrated condition. Changes of temperature which cause the minerals composing a rock to expand and contract unequally and the freezing of absorbed water are important agencies tending to fracture rocks which are exposed to the air or but thinly covered with soil. A depth of a few feet of soil, however, checks this action, so that the deep decay so frequently to be observed can be safely ascribed to the chemical action of percolating water. The process is hastened by the presence in the water of organic acids, derived principally from the humus of the surface soil. The disintegration and decay of rocks that are sheltered from changes of temperature is brought about to a

[1] I. C. Russell, Subaerial deposits of the arid region of the United States: Geol. Mag. (London), Vol. VI, 1889, pp. 289-295, 342-350.

[2] Washington State Agricultural College and School of Science, Experiment Station, Pullman, Washington, Bulletin 13, 1894, by Elton Fulmer and C. C Fletcher. University of Idaho Agricultural Experiment Station, Bulletin 9, 1894, by C. W. McCurdy.

VIEW OF PULLMAN FROM THE AGRICULTURAL COLLEGE, LOOKING NORTHWEST.

considerable extent by the removal of some of their constituents in solution. This process allows the grains and crystals which remain unaltered or are but moderately changed to fall apart. We should expect, therefore, that residual soils would contain less of soluble constituents than the parent rock, and consequently a higher percentage of the more insoluble constituents.

Samples of the basalt and of the subsoil and soil resting on it were collected by the writer and submitted to George P. Merrill, curator of the department of geology in the United States National Museum, for special study. Chemical analyses of three of the samples are presented below. The analysis of basalt is of a fresh and unaltered sample, being in fact a part of the specimen of which the mineralogical constituents are given on page 44; the subsoil is from a depth of 30 feet in a railroad cut near Dayton; the surface soil was taken from a depth of about 2 feet in a wheat field near the same locality.

Analyses of basalt, soil, and subsoil from near Dayton.

[Analyst, George P. Merrill.]

Constituents.	Basalt.	Surface soil.	Subsoil.
Silica, SiO_2	47.85	63.58	65.89
Alumina, Al_2O_3 / Iron oxide, Fe_2O_3	34.38	22.36	22.19
Lime, CaO	8.27	2.76	2.36
Magnesia, MgO	4.43	1.82	1.85
Potash, K_2O	1.33	2.27	2.36
Soda, Na_2O	2.55	2.02	2.08
Loss on ignition (principally organic matter)	0.95	4.37	2.60
	99.26	99.18	99.33

Merrill states:

All of the material analyzed was first dried at 100° C. The analyses are not as detailed as I would like to make them, but are all that the limited time permits. Perhaps the most striking fact in the analyses is the similarity in composition between the surface soil and that from a depth of 30 feet; almost the only essential difference being, apparently, the larger percentage of volatile matter of the surface soil. Not having as yet separated the iron and alumina, I am unable to account for the apparent loss of these constituents shown. From previous analyses I am led to suspect that the iron oxides have been very largely removed. I am unable as yet to account for the apparent increase in potash in the decomposed materials. It is possible, though hardly probable, that this is due to errors in analysis.

In reference to the apparent increase in potash in the decomposed material, I wish to state that there is no reason for supposing that

alkaline or other fertilizers have ever been applied. Possibly the stubble of the wheat fields may have been burned, but this would only return to the surface soil a part of the mineral constituents derived from it in the growth of the grain.

The close similarity between the composition of the subsoils, given above, and of the rock beneath it, is striking. All of the constituents of the rock except the silica and alumina are classed among the more soluble of the substances present in the earth's crust. The readiness with which they may be removed from rock by the process of solution is influenced, of course, by the manner in which they are combined, but the study of the products of rock decay has shown that lime, potash, magnesia, soda, etc., are much more readily removed than silica and alumina. The analyses given above indicate no departure from this rule except in the case of the potash. The soil analyses show that there has been a loss in all of the constituents of the original rock except silica, alumina (?), and potash. The increase in the percentage of potash, as remarked above, is surprising, and as yet unaccounted for. Organic matter and water have been added. The former may reasonably be supposed to have been derived from humus, while the latter indicates that some of the minerals have taken up water and changed to what is termed a hydrated condition. If we omit these added constituents and recalculate the analysis, it will appear that the percentage of silica in the soil is 67 per cent, a decided increase over the similar constituent in the rock, and that each of the other constituents is proportionately increased.

Several analyses of soils from the basaltic plateau, given in the bulletins of the agricultural experiment stations mentioned above, show that the one just quoted is typical and represents about the average composition of the soils of the wheat lands. The analysis of basalt also is of a normal sample of that rock.

The results of a chemical study of the soils and of the basalt are, then, in harmony with what is revealed on comparing the mineralogical composition of the basalt with that of the soils, and sustain the conclusion that the soil has been derived from the rock which it overlies, and also that the disintegration is due, in part at least, to the solution of the more soluble constituents of the parent rock. The loss in bulk, due to the removal of portions of the more soluble constituents, is counteracted to a considerable extent, however, by the hydration of some of the minerals and by the addition of organic matter. This is an interesting fact, as it indicates that there has been at most but a moderate lowering of the surface of the plateau by the removal of matter in solution. Indeed, as the soil is far more open and porous than the parent rock, there has been a tendency toward an actual increase in the elevation of the surface of the plateau. How much this rise of the surface level has been counteracted by stream and wind erosion

remains to be determined. The fact that water percolating through soil leads to the removal in solution of some of its constituents is well known, and has been fully recognized in the case of the soils of Washington by Professors Fulmer and Fletcher, of the Washington State Agricultural College, as is shown in the following quotation:[1]

Results of a large number of analyses have shown almost conclusively that soils in a reigon of abundant rainfall contain less lime than soils in arid regions; providing, of course, that neither are underlaid by or in the vicinity of limestone formations. [It will be shown below that this exception need not necessarily be made.] This fact is well verified in the case of our soils east and west of the Cascade Mountains, the average lime constituent of the former being three times that of the latter. This is specially significant in view of the fact that nearly all the soils of eastern Washington are derived from black basaltic rock.

With the samples analyzed so far, it seems almost as if the lime percentages are inversely proportioned to the amount of annual rainfall.

For example, we find the following relations:

Lime percentages.	Annual rainfall.
1.2127 0.9790 1.7580	About 8 inches.
1.0814 1.1800 0.7810 0.9300	20 to 22 inches.
0.6550 0.7690	24 inches.
0.3625 0.4315 0.1303	48 inches.
0.1090 0.0829	76 inches.

It will be interesting to note whether future analyses will reveal this same relation between the rainfall and the lime content of our soils.

The origin of soils from the disintegration and chemical change of rocks is well known, and there is nothing novel, so far as general principles are concerned, in the interesting statements just quoted in reference to the relation of the chemical composition of soils to climatic conditions.[2]

One of the most remarkable instances of the decrease in the soluble constituents of a rock when it passes into soil, given in the papers just referred to, occurs in the limestone region of the western part of Virginia, which, as is known to me from personal observation, is representative of a vast area in the South Atlantic States. The limestone referred to in general yields on decomposing about 1 per cent of insol-

[1] Washington State Agricultural College and School of Science, Experiment Station, Bulletin 13, pp. 39-40.

[2] The processes of rock disintegration and decay, the formation of soils, their variation under diverse climatic conditions, etc., have been discussed by the present writer in Bulletin No. 52 of the United States Geological Survey. A highly instructive analysis of the same phenomena, by George P. Merrill, of the United States National Museum, may be found in volume 4 of the Journal of Geology, published at the University of Chicago. References to many other papers on the same subject are given in these essays. See, also, A Treatise on Rocks, Rock-weathering, and Soils, by George P. Merrill, The Macmillan Company, 1897.

uble residue which is available for making soil. Analyses illustrating this are here inserted:[1]

Analysis of Trenton limestone and of the residue left by its decay.

[Analyst, R. B. Riggs.]

Constituents.	Unaltered limestone.	Residual clay.
Silica, SiO_2	0.44	43.07
Alumina, Al_2O_3	0.42	25.07
Iron oxide, Fe_2O_3		15.16
Lime, CaO	54.77	0.68
Magnesia, MgO	Trace	0.03
Potash, K_2O	Not determined	2.50
Soda, Na_2O	Not determined	1.20
Carbonic acid, CO_2	42.72	0.00
Water, H_2O	1.08	12.98
Total	99.43	100.64

The residual soil left by the nearly complete solution of limestone at the locality from which the sample analyzed was taken is a tenacious reddish clay, and is so poor in lime that calcined limestone is found to be a desirable fertilizer.

The change from basalt to residual soil on the surface of the great plateau of southeastern Washington is accompanied by less change in chemical composition than in the case cited of the formation of soil from the weathering of limestone, for the reason that so large a proportion of the basalt is composed of silica.

It seems, therefore, both from a comparison of the mineralogical character of the fragments composing the soil with the nature of the minerals composing the basalt, and from a study of the chemical composition of the unaltered rock and of the soil, that the subsoil is the result of the disintegration and decay of the country rock. The surface soil is of the same character as the subsoil, except that organic and atmospheric matter and volcanic and probably cosmic dust have been added.

An unexplained fact under this hypothesis is the presence in the subsoil of the minute and nearly vertical tubes previously described.

TOPOGRAPHY OF THE WHEAT LANDS.

The widely different ideas of the topography of southeastern Washington that one might obtain from traveling through the canyons and from a journey over the plateau surface have already been referred to. It is to the peculiar topography of much of the surface of the

[1] Bull. U. S. Geol. Survey No. 52, 1889, p. 24.

plateau where practically unaffected by the deep dissection accomplished by the larger streams that attention is here directed.

The surface of the plateau in some regions is nearly as level and featureless as the prairies of Illinois, while in other portions it is diversified by hills and valleys, and in its native state, when covered with bunch grass, was a rolling prairie. South of Snake River, especially on the portions of the plateau which remain between the various branches of Touchet, Alpowa, and Asotin creeks, the flat plateau-prairie lands are well displayed. North of Snake River, in the Palouse country, the rolling or hilly prairie predominates over extensive regions.

There is a certain relation between the smoothness or roughness of the surface of the plateau and the arrangement of the streams, but I doubt if this is the sole reason for the contrast between the smooth surfaces of the fragments of the plateau between the deep canyons south of Snake River and that of the hill plains to the north. Where the streams flow across the plateau they have excavated deep canyons, with comparatively few lateral branches. The rain falling on the deep soil of the plateau is absorbed and percolated away. It is thus robbed of its power to erode. Under these conditions surface channels, like those so common in many regions having a clayey soil, are not formed. At a distance from master streams, where the subdrainage was less perfect, the soil seems to have become saturated, and rills and rivulets appeared on the surface and flowed to brooks, and these to larger streams. The soil in such regions has been carved into hills and ridges, with hollows and shallow valleys between. The hills and valleys of the rolling prairie region, as will be shown below, were still further modified by the wind.

When one gains a comprehensive view of the surface of the plateau—as, for example, from the borders of the Blue Mountain uplift or from the sharp summit of Steptoe Butte—it is seen that the controlling features in the topography of the surrounding country are due to stream erosion. A map of the plateau would show that where the broad, level, plain-like features predominate, the land is incompletely drained. There are no rill and brook channels ready to carry off the rain water, should it fall in sufficient abundance to form surface streams. In the hilly portion of the plateau, however, as in the Palouse country, there are countless small valleys and depressions that join large channels and everywhere favor the running off of surface water. The portions of the plateau's surface that have not been etched by stream erosion are, in the language of geographers, young land areas, while the roughened surface of the rolling prairies furnishes examples of youthful topography, or, in this instance, of arrested development in an early stage of growth.

These conclusions may not seem well founded to those who are aware that the portions of the plateau between the deeply cut canyons are

without surface streams. Even where the plateau surface is hilly and the numerous minor valleys and depressions favor complete drainage, there are not only no streams at any time during the year, but no stream channels in the valley bottoms. There was formerly a time, however, when precipitation was more abundant than now, and the land in what is now the rolling prairie was sculptured by a multitude of rills and brooks.

The hilly prairie is characteristically developed in eastern Washington, north of Snake River, and probably extends to Spokane River. The most typical portion, so far as I can judge from personal observation, is in the region drained by Palouse River. The towns of Pullman and Garfield are surrounded by the characteristic hills here referred to, and from Kamiack and Steptoe buttes one can look down on tens of thousands of acres of hilly and undulating wheat lands, which in a state of nature formed a vast, hilly prairie.

In this region hills with smooth, even slopes and rounded tops and crests, rising in general from 20 to 80 feet above the adjacent depressions, occur in thousands. Many of the hills rise to one general level, but none reach above it. The fact that the roughened surface of the plateau is a broad plain is always apparent in a general view.

One feature of the hills which especially attracts attention is that they are usually steep on the northeast side and slope gently toward the southwest. The steeper sides frequently have a slope of 20° with a horizontal plane, and in many instances are slightly concave when seen in profile, while the more gently sloping sides descend at angles measuring 5° to 8°, and are frequently gently convex. These features may be recognized in the photographs of characteristic portions of the hilly plateau forming the accompanying plates.

In many instances the extremities of ridges which present a steep slope to the northeast terminate at each end in tapering prolongations extending northeastward, which curve slightly toward each other and partially inclose a hollow. Many of these amphitheater-like inclosures may be seen in the northeast sides of the hills about Pullman and Garfield.

From what has been stated, the fact will be recognized, I think, that many of the hills of the plateau are similar in form to the hills of drifted sand termed "dunes."

The dune-like shape of many of the hills about Pullman was first pointed out to me by President E. A. Bryan and Prof. C. V. Piper, of the Washington State Agricultural College and School of Science. These gentlemen also stated that the prevailing winds of that section of the country are from the southwest. The hypothesis was thus suggested that the soil of the plateau, of which even the highest hills are composed, has been blown by the prevailing winds and piled up in part in dune-like forms. The similarity in physical properties between the fine soil of the wheat lands and the equally fine, dust-like deposits

in China, termed loess, and believed by some geologists to be wind-borne deposits, as previously suggested, seemed also to give weight to the hypothesis that the hills under consideration are of eolian origin. The idea has been suggested that the soil of the wheat lands has been brought by the winds from a desert region to the southwest, but there is no extensive desert area in that direction, and besides, as we have already seen, the mineralogical and chemical composition of the soil and its transition into disintegrated rock and finally into solid basalt shows that it originated in the place where we now find it.

The prevailing and characteristic dune-like shapes of the hills is sufficient evidence, however, that their contours have been modified to some extent by wind action. As already stated, the main topographic features, even where the dune-like hills are best displayed, are such as are produced by erosion. The partially filled depressions between the hills have continuous slopes, which would furnish natural and unbroken channels of escape should the rainfall become sufficiently abundant to initiate surface drainage.

The best explanation I can offer of the origin of the hilly topography of the less deeply dissected portions of the basaltic plateau is that the principal changes in the relief of the surface of the originally flat and featureless plateau are due to stream erosion at a time when the precipitation was more copious than now, and that with a decrease in precipitation the forms of the hills, left in relief by the excavation of the valley, were modified by the prevailing winds. The fine soil was blown from the southwest sides of the hills, which trend northwest and southeast, and accumulated on their leeward slopes. But this action has not been carried far enough to obliterate or to greatly modify the topographic forms due to previous stream erosion. In no instance during a careful search extending over several days was I able to find a single valley or depression which was not connected with the present lines of drainage by valleys and dells that would admit of complete surface drainage in the case of a heavy rainfall. This evidently would not have been the case if the wind had been the controlling agency in modeling the relief of the plateau's surface.

The steep northeast slopes of the hills, as already mentioned, frequently have concave profiles. These curved slopes suggest the profiles of volcanic cones formed of fragments blown out of a volcano and falling about its sides. They are the reverse of the convex "weather curves" produced by the removal of the surface of an uplift in the process of weathering. The concave sides of the hills have such profiles as would be formed by material blown over their crests and accumulated on their lee sides; while their summits and southwest slopes present such profiles as normally result from weathering.

Excavations in the hills have in some instances shown a greater depth of fine, dust-like soil on the lee side of their crests than on the

windward side. In some cases a clayey subsoil is met with at a depth of a few feet on the southwest side, while on the opposite side a deep loess-like soil prevails. This has been noticed in the college farm at Pullman, as I have been informed by President Bryan, where clay interbedded with the Columbia lava has influenced the character of the soil. In railroad cuts deposits of fine, dust-like soil having a depth of 30 or 40 feet have been observed in several instances on the northeast side of hills; while in similar cuts on the southwest slopes of corresponding hills they would be less thick. Rock exposures are perhaps more numerous on the northern sides of canyons than on their southern sides, owing to the accumulation of soil in the lee of their southern walls, but I am not aware that there is a marked tendency in this direction.

I have thought, also, that a difference is observable between soil that has been moved and redeposited by wind and soil that remains in place, but the differences between the two are so slight and their junction so indefinite that no sharp line of division can usually be recognized.

It is possible that the vertical tubes described on a previous page occur only in the soil that has been moved by the wind. The tubes referred to are certainly abundant in the soil on the northwest slopes of hills, but whether they are absent in soil that has not been disturbed remains to be proven.

The valleys in the surface of the hilly plateau have characteristics, also, which are novel to one familiar only with a well-watered country. The great majority, and in fact nearly all, of the valleys of the plateau, except such as are traversed by streams flowing from the bordering mountains, are flat bottomed and without stream channels. These valleys are usually deeply filled with fine soil of the same character as that forming the adjacent hills. In cross section the valleys are level-floored, but in longitudinal section their even surfaces would show a gentle inclination toward the deeper valleys to which they lead, and in which there are streams flowing from the neighboring mountains.

As stated in connection with the description of other climatic features of eastern Washington, the precipitation is small, averaging about 16 inches annually. The deep, fine, porous soil absorbs the rain as it falls and the water formed from melting snow. It is to this fact that the possibility of raising wheat and other cereals on the broad plateau is due. All of the annual precipitation except what is returned to the atmosphere by direct evaporation, as when snow vanishes before a warm wind without melting, is not only absorbed by the soil, but is retained, to a great extent, near the surface. In excavations in excess of 15 or 20 feet on the plateau surface, I have been informed, dry soil is usually reached.

It is a striking fact, especially on the hilly portion of the plateau,

that even the steepest slopes, in many instances having an inclination of from 20° to 30°, are without rill marks. This is not because there is a mat of roots binding the soil together and thus preserving it from washing, for the surfaces of the plowed hillsides are smooth and unscarred by gullies. It is the custom generally throughout the wheat-growing region of eastern Washington, as already stated, to harvest but one crop in two years from a given area. The farmers have learned that by this method they can obtain about as much grain as if the land were sown and harvested each year. Inquiries as to the reasons that make this possible have not elicited satisfactory answers. The suggestion has occurred to me, however, that possibly the evaporation from a plowed field is so much less than from a field covered with growing grain that by plowing the land and leaving it unsown every other year a greater store of moisture is secured for the alternate years, when a crop is raised. This suggestion is in harmony with the well-known fact that the conditions which are favorable or unfavorable to agriculture on the basaltic plateau, with reference especially to moisture, are delicately balanced. When a slight increase over the average annual precipitation is experienced, an abundant harvest is secured; but if the precipitation—particularly the amount of snow—is small, the effect is seen in a diminished harvest. This statement must be qualified, however, since the amount of precipitation is not the only important climatic factor on which the success or failure of the harvests depends. In winter the snow, although perhaps abundant, is sometimes evaporated by warm, dry winds, without melting, and therefore fails to add to the store of moisture in the soil. Hot winds occur sometimes also in spring and early summer, and wither the young grain.

The semihumid character of the climate of eastern Washington, shown by the conditions limiting the cultivation of cereals, leads naturally to the consideration of the possibilities of irrigation and of artesian water supply.

IRRIGATION.[1]

Region south of Snake River.—To a person traveling through southeastern Washington, a truly astonishing feature of the country is the great quantity of water flowing from the Blue Mountains. I have already directed attention to the fact that on what has been termed the wheat-land plateau all of the water that reaches the soil is absorbed. The same is true among the Blue Mountains, which are in reality a more elevated plateau of the same general character that has been deeply dissected by stream erosion. This uplift furnishes a splendid example of mature drainage—that is, a drainage system which has cut down its principal channels approximately to the level

[1] For data on water supply and irrigation from Umatilla River, see Bull. No. 131, Report of Progress of the Division of Hydrography, United States Geological Survey, for 1893 and 1894, pp. 69-73.

of the master stream into which they discharge. The principal streams have developed innumerable lateral branches, so that the entire region is well drained. With the deepening of the stream channels there has been erosion of the interstream spaces, and instead of flat-topped tables, only sharp, serrate ridges remain. These stream channels are no older than the less well-developed channels on the lower plateau, but the advantage gained from the greater elevation of the land has given the flowing waters greater velocity and enabled them to progress with their appointed task more rapidly.

Rock disintegration and decay has kept pace with, and in recent times exceeded, denudation, and every depression and every shelf on the canyon walls is filled and covered with soil. This soil is of the same character as that of the wheat lands, except for the frequent occurrence of angular rock fragments in it. All portions of the intricate system of ridges composing the so-called mountains, except the actual cliffs and precipices, are thus soil covered.

Among the mountains, as on the hill slopes of the wheat lands, there is an absence of rill marks. Earth slopes having a descent of fully 45° are usually without rill marks or scars of any kind due to erosion. The few miniature water courses that do occur on such slopes are the result of the infrequent storms known as "cloudbursts." The water absorbed by the porous soil passes down into the jointed and frequently scoriaceous basalt below, and by slow percolation feeds perennial streams.

As already described in the section of this report devoted to drainage, and as shown on the accompanying map, there are many creeks, some of them having the volume of rivers, radiating in all directions from the Blue Mountains. Each of these streams flows throughout the year and carries a never-failing flood of clear, cold water down to the parched valleys below. Each of these streams, with the exception of the Grande Ronde, can be utilized to its full capacity for irrigation.

The Grande Ronde in all of its lower course, as already shown, flows through such a rugged canyon that scarcely any land can be economically irrigated by it. Here and there along the main river, however, and on its branches, are small areas, some of which may be watered from the river itself or by lateral streams. The productiveness of these areas makes them especially valuable for orchards and gardens. It is in these sheltered recesses that fruit, vegetables, tobacco, etc., may be raised, while the canyon sides and much of the plateau surface, some 3,000 feet above, is available for stock ranges. Toward the headwaters of the river broad areas of the plateau surface still remain and are clothed with forests. This land, when cleared, will produce wheat, but it is to be hoped that much of it will be retained in nearly its natural condition as a forest preserve.

The other streams referred to, which radiate from the Blue Moun-

tains of Washington and adjacent portions of Oregon, flow through canyons, but in most instances are bordered by narrow flood plains, elevated but a few feet above their channels, or by ancient terraces, as in the case especially of the Walla Walla and several of its branches. Of the streams under consideration, the ones least favorably circumstanced for irrigation purposes are Asotin and Alpowa creeks. But even these can be utilized, as is shown by the canal described below, which leads the water from Asotin Creek about the face of the bluffs forming Snake River Canyon and delivers it to irrigable lands opposite Lewiston. The Alpowa flows for a large part of its course in a narrow gorge, but near its mouth and along the adjacent portion of Snake River there are lands so situated that they can be irrigated.

In the absence of a topographic survey of the Blue Mountains and adjacent regions, it is not practicable to designate in a report of the character of the one here presented what lands can be economically irrigated or where storage reservoirs can be constructed to the best advantage. From the point of view of the engineer, however, it seems practicable not only to utilize for irrigation purposes all of the water flowing from the Blue Mountains in summer, but to store a large portion of the winter run-off and hold it for use during the growing season.

As is only too well known, the main obstacles to the full utilization of the water now running to waste in many arid regions—and southeastern Washington is no exception to the rule—is the rivalry of individual owners of land and of water rights. No general plan of using the summer flow from the Blue Mountains or of storing a part of the winter run-off can be carried out, however practicable it may seem to the engineer, until a large number of the owners of land in the region to be affected give their consent and cooperate in carrying out far-reaching plans for the public good.

In writing of the possibilities for irrigation in the region to the north of the Blue Mountains—and what has been said will apply also to large areas in the adjacent portion of Oregon—attention has been directed mainly to the canyon bottoms and to the ancient stream terraces. The engineer sees possibilities, also, in the direction of irrigating some portion of the wheat-land plateau between the deeply sunken stream channels.

To the northward of the Blue Mountains, more especially in Garfield and Asotin counties, the plateau surface rises gently toward the mountains, and in some instances could be watered by diverting the streams near their sources and before their channels became much depressed below the general level of the plateau. Little attention has been directed to the possibility of diverting the waters of the several branches of the Asotin, Alpowa, and Tokanon in their upper courses, and conducting them into the broad areas between the deep canyons of the main streams lower down, but this seems feasible to one making

a hasty examination of the region, especially if storage reservoirs can be established. The possibilities here referred to are illustrated at Anatone, about 14 miles southwestward from Asotin, where the water of George Creek, one of the tributaries of Asotin Creek, has been diverted with but trifling expense and carried to a nearly level area of rich wheat land conveniently situated for irrigation. This small experiment certainly suggests other possibilities in the same region. There is reason to believe that a careful survey would show available reservoir sites near the sources of several of the mountain streams, so situated that broad areas of the plateau could be watered from them.

At present little use is made of the water flowing from the Blue Mountains in comparison with what is possible from an engineering point of view. Small ditches have been made in a number of instances, particularly in the neighborhood of Walla Walla, for the purpose of irrigating gardens and orchards. In the lower portion of Walla Walla River about half a dozen water wheels arranged with buckets are in use. These raise the water from the river to a height of 15 feet and allow it to flow in ditches to orchard and garden lands. Each wheel is said to be capable of irrigating from 8 to 10 acres of land. In addition to these uses of the streams for irrigation by individuals a few attempts have been made by companies to construct irrigating canals.

What is known as the "Willis ditch," constructed by the Willis Land and Improvement Company, is taken out of the Walla Walla at the mouth of Mill Creek. The head of the ditch is in the southeast quarter of section 31, township 7, range 35, and extends westward 4½ miles, but is surveyed for 10 miles farther. This canal is 20 feet wide at the top and now carries 16 to 18 inches of water, but when in full operation is planned to carry a stream 2 feet deep. I have been informed that it now irrigates about 4,000 acres of land.

The "Hawley ditch" leaves the right bank of the Walla Walla at Raymo, and is 8 miles long, although only 4 miles are now in operation. It is said to carry 60 cubic feet of water per second, and to irrigate about 1,000 acres. When completed it is estimated that it will irrigate between 1,500 and 1,600 acres.

On the opposite side of Walla Walla River the Walla Walla Irrigation Company has constructed a ditch, beginning farther upstream, and now completed for about 4 miles, but it is not in operation. If the present plans are carried out, this ditch, when finished, will be in the neighborhood of 20 miles long and capable of irrigating some 4,000 or 5,000 acres of land.

In the canyon of Touchet River, about 4 miles above its mouth, a ditch has been constructed on the left bank of the stream. One and one-half miles below its head it is divided, one half being carried across the river to the left bank. Its capacity is about 60 cubic feet per second, and at present it is said to irrigate 2,000 acres.

Such information as is here given concerning the more comprehen-

sive plans that have been made for using the water of Walla Walla River and its branches was furnished by various gentlemen interested in the improvements mentioned. More detailed information could not be obtained, for the reason, in part, that some of the companies engaged in this work are involved in litigation growing out of the complex problem of riparian rights.

Snake River Canyon.—Snake River, although a magnificent stream, is not available for the irrigation of the surface of the plateau through which it flows, for the reason, as we have already seen, that it is deeply sunken in the rocks of the plateau. There are several areas in the bottom of the canyon, however, from a few acres to 300 or 400 acres in extent, which can be irrigated from the main river or by the waters of some of the tributary brooks and creeks. The soil at the localities referred to is river sand, exceedingly light and porous. It contains much mica and considerable lime, due in part to the presence of shells of fresh-water mollusks, and when irrigated is well adapted to fruit culture. Some of the finest fruit raised in Washington is grown on these sand bars, deep in the shelter of canyon walls.

The boldest scheme in the way of irrigation yet put into operation in southeastern Washington is one that was practically completed in 1896 by the Lewiston Water and Power Company, on the west side of Snake River, below Asotin. The canal referred to diverts the water of Asotin Creek, and carries it along the precipitous south side of Asotin Creek Canyon, and about the face of a bluff at the junction of this canyon with the broader canyon of Snake River, and northward along the steep side of the river canyon at an elevation of approximately 600 feet above the river. The canal is designed to furnish water for irrigating about 3,500 acres in Asotin County, Washington, and also 4,000 acres in Idaho, near Lewiston. The following facts concerning this important enterprise have been kindly furnished by Messrs. C. C. Van Arsdol and E. H. Libby, of the Lewiston Water and Power Company:

The water is taken from Asotin Creek about 6 miles above its junction with Snake River, at an approximate elevation of 665 feet above Snake River, and is conducted 6¼ miles along the north slope of Asotin Creek by a flume 6 feet wide and 3½ feet in depth, with a grade of 10.56 feet per mile; thence to a point north of Swallows Nest Rock, a distance of 8 miles by canal, 6 feet wide on bottom, 16 feet wide on top, and 5 feet deep, with a grade of 2.12 feet per mile. Estimated capacity, 127 cubic feet per second. From a point near Swallows Nest Rock the distributing laterals diverge.

In the canyon of Snake River, above Asotin, there are narrow, detached strips of moderately flat land, having a width in some instances of 200 or 300 yards, composed of river silt and sand. These are nearly all on the west bank of the stream, and are bounded on one side by the swift-flowing waters and on the other by mountain-like walls of basalt from 2,000 to 3,000 feet high. A few of these narrow

areas are now irrigated from small streams that come down the gulches in the canyon wall and are supplied by springs. In this portion of the canyon of Snake River the water of the river itself is not used for irrigation.

Below Lewiston there are also several localities where silt and fine micaceous sand brought down by the river has accumulated in sheltered portions of the bottom of the canyon. The largest of these areas now under cultivation is at the mouth of Wawawai Creek, which supplies water for its irrigation. At this locality about 300 acres are occupied by fine orchards of peaches, pears, prunes, etc. These orchards are wonderfully productive, and furnish fruit of large size and excellent quality. Between Wawawai and the mouth of Snake River there are about half a dozen localities at which from 8 to 14 acres of fruit land are under cultivation. The total amount of land in this section now being irrigated is in the neighborhood of 100 acres. At most of these localities water for irrigation is raised from the river by pumps operated by undershot water wheels, current wheels, located on rafts, as shown in Pl. V. These wheels are, I believe, all of one pattern. They are 18 or 19 feet long by 9 to 11 feet in diameter, and vary in effectiveness with variations in strength of current. One, owned by Mr. H. Gilbert, situated in section 26, township 11, range 33, at the time of my visit, August 19, was operating two suction pumps, each of which made 20 strokes per minute, and lifting about one-half gallon of water to a height of 27 feet at each stroke. At more favorable stages of the river the amount of water raised is doubled. The water is carried away in a small flume and irrigates about 1,000 fruit trees.

The difficulties that have to be contended with in this comparatively inexpensive method of irrigation arise principally from variations in the height of the river. The portion of Snake River here considered rises during floods from 20 to 32 feet above the mean low-water stage. The scows carrying the water wheels and pumps have to be moved from time to time to suit the varying height of the water. In winter the scows must be removed from the river to prevent destruction by floating ice. Dangers from driftwood have also to be guarded against, especially during high water.

The river sometimes rises during floods to within 3 or 4 feet of the cultivated lands, and there is danger at such periods that the river will remove the deposits previously made and thus destroy industries which it has required years to establish. This danger can probably be counteracted in many instances by planting willows and alders along the river banks. The inhabitants in Snake River Canyon should certainly take every possible precaution against unusually high floods in the river, as there is but a small margin between the usual spring rise and the surfaces of the sand bars where orchards and houses are located.

WATER WHEEL LIFTING WATER FROM SA' 10N RIVER FOR IRRIGATION.

The Palouse country.—The surface of the wheat-land plateau north of Snake River, drained principally by Palouse River, is, as we have seen, a rolling, hilly region. Irrigation is there impracticable, except in the larger valley bottoms. Scarcely any irrigation is now practiced, and my examination of the region was too hasty to admit of an opinion in reference to what may there be possible. It seems probable, however, that here, as in many other portions of the arid and semihumid regions of the United States, the storage of water must eventually be resorted to.

A topographic map.—To those interested in the development of the many and varied industries of Washington, I venture to earnestly recommend the early completion of an accurate topographic map of the State. Such a map, in the sheets covering the more thickly settled areas, and where irrigation is desirable and practicable, should be on a scale of 1 mile to the inch, with contour lines showing relief of surface, drawn with 20-foot vertical intervals.

A knowledge of the drainage and topography or surface relief of a State is an important basis not only for irrigation but for planning country roads, railroads, canals, flumes, town water supply, etc., and in learning the best way to bring mines, timber, and agricultural lands in communication with markets. It is safe to say that the cost of nearly all public improvements and of many private enterprises would be greatly reduced if an accurate map of the State were available on which to base plans and estimates. The educational value of such a map, especially to school children in giving them a knowledge of home geography, is by no means the least of the useful purposes it would serve.

ARTESIAN WATER SUPPLY.

The small rainfall of southeastern Washington, and the fact that it is impossible to irrigate by far the larger part of the grain lands, or, in many instances, to obtain wholesome water for towns and even for farmhouses, from streams or ordinary surface wells, have led to the hope that a subterranean water supply might be discovered. In a number of instances marked success has attended the drilling of artesian wells, particularly in the eastern portion of Whitman County, and stimulated a desire to have similar experiments made elsewhere.

GENERAL CONDITIONS.

Before the expense incident to the drilling of deep wells is incurred it is desirable to give attention to at least two considerations: First, the conditions which render the obtaining of artesian water possible, and second, the geology of the region where it is proposed to drill a well. After a study of these questions in reference to a given locality one may predict with considerable confidence what measure of success is possible.

What are termed "the requisite and qualifying conditions of artesian wells" have already been fully explained in the publications of the United States Geological Survey,[1] and it does not seem necessary to restate them at length in this report.

Briefly stated, an artesian well is one in which water rises under the influence of the pressure of water at higher levels. The suggestion that water sometimes rises in a well or boring on account of gas pressure need not be discussed at this time.

In an artesian well the water sometimes rises to the surface and overflows, or it may be under sufficient pressure to form a fountain-like jet above the surface; in other cases the water rises some distance in the well, but fails to reach the surface. In all these instances the well is classed as artesian. The question of surface flow is determined not only by the pressure acting on the water but by the elevation of the surface at the mouth of the well. For example, a well drilled in a valley might reach a water-charged layer of rock in which the water is under sufficient pressure to cause it to rise fountain-like above the surface; while a well drilled on a neighboring hill and reaching the same water-bearing layer would be only partially filled. If in such instances the casing or pipe of the lower well be continued upward, its top remaining open, the water will rise within it to the same level at which it stands in the well drilled on the neighboring hill; that is, the water is under the same pressure in each instance. I make this explanation in reply to numerous questions asked me during my field studies, as to whether an artesian well is necessarily a flowing well or not. In brief, an artesian well is one in which water rises under pressure; if the water overflows the surface, it is convenient to designate it as a flowing well.

In order that water may rise in a tube drilled in the earth it is necessary for it to be under pressure; in other words, the water must be confined so that it can not flow away and thus relieve the pressure. The most common conditions under which this happens are these: Certain layers of rock of loose texture, as sand and sandstone, become water-charged, and the water is confined in them by other layers above and below which are impervious to water, such as clay. If a water-charged layer of sand between two layers of clay is inclined, the water will percolate through it. If the central portion of such a water-charged sheet is depressed, the water in the surrounding portions will tend to flow toward the depressed central area. The water in the central portion will then be under the pressure of the water in the more elevated portions of the porous layer. Evidently, under such conditions, if a hole is made from the surface through the upper layer of clay, it will allow the water to rise to the surface, or until it stands as high as the lowest outlet in the rim of the basin. These

[1] The requisite and qualifying conditions of artesian wells, by T. C. Chamberlain: Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 125-173. Residents of Washington may find it profitable to consult also: "General principles pertaining to artesian water," in A Geological Reconnoissance in Central Washington, by I. C. Russell: Bull. U. S. Geol. Survey No. 108, 1893, pp. 32-36.

conditions are illustrated in the following ideal section across an artesian basin:

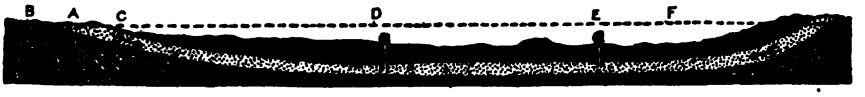


FIG. 2.—Ideal section illustrating the chief conditions of artesian wells. A, a porous stratum; B and C, impervious beds below and above A, acting as confining strata; F, the height of the water level, "artesian head," in the porous bed A, or, in other words, the height of the reservoir or fountain head; D and E, flowing wells springing from the porous water-filled bed A. (After T. C. Chamberlin.)

In nature we find examples of what, for convenience, may be termed incomplete artesian basins; as, for instance, when an inclined pervious bed, a layer of sand, we will say, thins out on its lower edge and allows the sheets of impervious rock above and below it to come together. An ideal example of this character is shown in the following cross section:

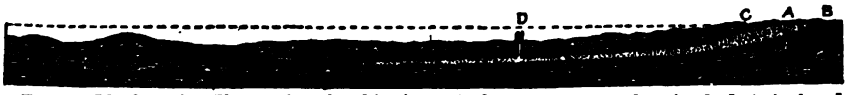


FIG. 3.—Ideal section illustrating the thinning out of a porous water-bearing bed, A, inclosed between impervious beds, B and C, thus furnishing the necessary conditions for an artesian fountain, D. (After T. C. Chamberlin.)

If the layer of sand is penetrated by a well drilled at D, the water will rise in an open tube to a height regulated by the pressure of the water in the sand above the locality where the well reaches it.

The source of the water that rises in artesian wells is mainly the precipitation on the edges of the pervious beds where they come to the surface. In some instances the porous beds are charged in this way at their outcrops, hundreds of miles from where the water is liberated by drilling wells.

The height to which water rises in an artesian well, or, in the case of a flowing well, the height to which it would rise in a tube open at the top, if properly attached to the well, is termed the "artesian head." This is illustrated in the waterworks of towns, where the water rises in the distributing pipes to the same level as the surface of the water in the reservoir from which it is drawn.

From this brief outline of the leading conditions which favor the possibility of obtaining artesian water it will be seen that the task of the geologist in this connection consists in ascertaining whether alternating sheets of pervious and impervious rocks exist in the regions he studies, and, if the requisite succession of beds is found, whether the beds are so inclined as to bring a portion of the water in the pervious layers under the pressure of other portions. In addition, the amount of rainfall and the quantity of water brought by streams to the outcrop of the porous beds; whether the impervious beds are broken; the changes which layers of rock undergo from one locality

to another; the depth to which the pervious layers have been eroded by streams; and several other limiting and qualifying conditions have to be considered and investigated.

LOCAL CONDITIONS.

In southeastern Washington and adjacent portions of Oregon and Idaho the rocks, as already described, belong in two series: First, the crystalline or metamorphic and igneous rocks, consisting principally of granite, schist, quartzite, and diorite, forming the mountains of western Idaho; and second, the lava sheets and interleaved sands and clays forming the wheat-land plateau and the Blue Mountains.

So far as the question of obtaining artesian water is concerned, we may dismiss the regions where the metamorphic rocks and diorite form the surface. The original bedding in these rocks has been almost entirely obliterated by the changes they have experienced, and there is no succession of porous and compact layers. The rocks have been folded and broken by joints, so that practically none of the requisite conditions for retaining water under pressure are present. The fissures and cavities in these rocks are probably, in many instances, water-filled, so that wells drilled at the proper localities might allow the water in them to rise and possibly to overflow the surface. But these cavities are irregular, and, as far as can be judged, seldom present the conditions just mentioned. It is impossible for anyone to predict where such water-filled cavities exist, and the drilling of a hole in the rocks with the hope of finding one is to take one chance in a million.

The areas where granite, schists, quartzites, and diorites are exposed or occur a short distance below the immediate surface are therefore to be avoided in all attempts to obtain artesian water.

In the region occupied by the Columbia lava the rocks, although for the most part of igneous origin, are in well-defined layers. Between the sheets of basalt, as the reader is already aware, there are layers of sand, volcanic dust and lapilli, and clay. This series of beds, although apparently horizontal over broad areas, is in reality in many localities slightly inclined. Conditions favorable to the hope of obtaining artesian water are thus suggested.

The basalt is not porous, except very imperfectly at the junctions of many of the layers, where it is scoriaceous, and it can not be considered as a pervious rock. It is traversed by innumerable joints and seams, and evidently could not retain water under pressure. In itself, therefore, the basalt presents no condition that would encourage the hope of finding artesian water.

When sheets of sand and clay intervene between the layers of basalt, and the series is slightly tilted, more hopeful conditions evidently result. These conditions are fulfilled in a belt of country, some 10 or 15 miles broad, along the eastern border of Washington, north of Snake River, and extending at least as far as the northern boundary of Whitman County, and possibly all the way to Spokane River.

The westerly inclination of the rocks in this section is extremely gentle, and, although not yet measured, may probably be taken at about 5 feet to a mile. The artesian head is consequently low, and it is only in the deeper valleys—which, however, have not been cut through certain strata of clay—that flowing wells can be obtained.

EXISTING WELLS.

The information here presented concerning the wells that have been drilled in southeastern Washington has been obtained from various persons who were especially interested in the results hoped for, but was furnished principally by Mr. A. L. Ebersol, of Garfield, Washington. Mr. Ebersol began his work as a well driller in the oil fields of Pennsylvania, and has had several years' experience in putting down wells under contract in Washington.

Wells at Pullman.—Pullman is situated partially in a narrow, steep-sided canyon, cut in the basaltic plateau by one of the several branches of Palouse River. The bottom of the now partially filled canyon is about 200 feet below the general level of the plateau. The college buildings situated near the summit of the hills overlooking the business portion of the town are 220 feet above the station of the Union Pacific Railroad, which, as shown by railroad surveys, is 2,340 feet above the sea.

Fifteen wells have been drilled at Pullman, some of them in the bottom of the canyon and others on its borders. Those in the bottom of the canyon, 11 in number, are flowing wells, but those on the sides of the canyon above an elevation of about 2,365 feet do not overflow; that is, the pressure on the water in the pervious stratum penetrated by these wells is sufficient to raise it to a level of about 25 feet above the canyon's bottom.

The hills bordering the canyon at Pullman are of basalt, which appears to be a single flow, and so far as can be ascertained by observation and the use of a pocket level is horizontal. Beneath this heavy sheet of basalt is a stratum of clay, 25 to 30 feet thick, the upper surface of which has been hardened and rendered dark in color by the heat of the basalt spread over it. Below the clay is a layer of basalt 60 feet thick; then comes a layer of granitic sand, which has been penetrated to a depth of about 12 feet without reaching the bottom. This sand is unconsolidated and abundantly water charged.

It is reported that some of the wells furnished artesian water as soon as the clay layer was penetrated and that the volume increased until the sand was reached. This seems to indicate that the water rose through fissures and seams in the basalt, but not with sufficient freedom to furnish the desired supply. The impervious layer is evidently the clay stratum, and the pervious layer is the loose, unconsolidated sand. Sand is thrown out of the flowing wells, and samples collected show that it is mainly quartz sand, with occasional fragments of granite and basalt and much mica. This material is mainly such as would

be furnished by the disintegration of the quartzite and granite forming the hills bordering the basaltic plateau on the east. With the quartz sand are mingled grains of basalt, which sometimes give it a dark color.

The first well drilled, that now supplying the Palace Hotel, as stated by M. C. True, the owner of the hotel, was finished in May, 1894. It has a total depth of 77 feet, and reached flowing water at 65 feet. It is 6 inches in diameter, and furnishes about 30,000 gallons per day. The well, beginning at the surface, passes through 12 feet of soil and cobblestone and 53 feet of solid basalt, and after passing through the basalt it reaches about 12 feet in the sand beneath. The elevation at the surface is that of the general level of the canyon bottom, or 2,340 feet. The water rises in pipes about 20 feet above the mouth of the well.

On the opposite side of the street from the Palace Hotel a well was drilled for J. R. Ruply in 1889 to a depth of 73 feet. This well is said to have been drilled in solid basalt, with the exception of the first 8 or 10 feet, which consisted of soil and loose rocks. The report fails to mention the stratum of clay which outcrops in the sides of the canyon near at hand, and which probably exists beneath the surface alluvium throughout the lower part of the town.[1] The Ruply well is 6 inches in diameter. It reached a stratum of micaceous sand, and water rose well above the surface, as is shown in the photograph here reproduced.

The well which supplies the town of Pullman was drilled in 1890, and is 6 inches in diameter and 84 feet deep. The surface level is practically the same as that of the Palace Hotel well. The section passed through is reported to be as follows: Surface soil, 3 feet; clay, 10 feet; basalt, 60 feet; gravel and sand with lignite, 11 feet. The bottom of the layer of sand was not reached. Water rose in an open pipe 20 feet above the surface, or to a level about 2,360 feet above the sea. No decrease in the pressure has since been observed. The water is raised by steam pumps to a reservoir on an adjacent hill and from there distributed for domestic and town purposes.

The three wells just described are typical examples of the eleven flowing wells now in operation in the lower portion of Pullman. The wells on the sides of the canyon, which were begun above the artesian head of the water in the porous stratum, are illustrated by the one which supplies the college buildings. The surface level at this well, as shown by measurements with an aneroid barometer, is 30 feet above the general level of the street in the lower portion of the town, or 2,370 feet above the sea. The well has a total depth of 144 feet, and is reported by Mr. Ebersol, the contractor, to have been all in basalt, except about 30 feet of clay. The clay layer is reported to

[1] In the report obtained of several other wells in Pullman all reference to this clay stratum was omitted. A possible reason for this omission is that the price of drilling is usually varied with the character of the material passed through.

ARTESIAN WELL AT PULLMAN.

have been reached at 65 feet below the surface. The section exposed in the valley of the canyon, however, indicates that the clay should have been first encountered at about 25 or 30 feet below the surface. Water rises to within 6 feet of the surface and is pumped to a reservoir which supplies the college buildings, situated about 200 feet higher than the surface at the well.

It does not seem advisable to record at this time all of the reports obtained concerning the wells at Pullman, as careful records of the character of the rocks passed through were not kept, and in some instances the reports obtained are unsatisfactory for other reasons.

The wells are all 6 inches in diameter. The contract price for drilling in surface earth and clay was in general $1 per foot, and in basalt $4 per foot. The water in all cases is beautifully clear, without occluded gases, and, with the exception of the Palace Hotel well, is soft. The water of the exceptional well has not been analyzed, but its taste suggests the presence of iron. None of the wells are cased, but much loss from leakage through fissures in the basalt is prevented by the clay stratum near the surface. The wells in the lower part of the town begin in the clay or in superficial deposits resting on it. It is to be expected that westward from Pullman, where the branches of Palouse River become deeper, the clay layer has been cut through, and that the conditions favorable for obtaining artesian water will be impaired, for the reason that basalt allows water under pressure to escape through fissures. In such instances it is evident that all wells should be cased down to the water-bearing sands.

Several of the wells at Pullman are allowed to flow, thus wasting a large volume of water and decreasing the pressure. If the blessings accompanying the discovery of an excellent water supply are to be maintained, all wells should be closed when not in use.

Wells at Moscow, Idaho.—At Moscow, Idaho, about 9 miles east of Pullman and near the junction of the Columbia basalt with the granite hills bordering it on the east, several wells have been drilled.

I have been informed by Mr. Ebersol and others that fourteen wells have been drilled since 1890, and that ten of these were flowing in 1891, but since then the pressure has so decreased that the water now stands 8 or 9 feet below the surface. The depth of these wells is in general about 100 feet, the first 50 to 60 feet being through loose material—the alluvial filling of the valley—and the remainder in basalt. Whether a layer of sand was reached or not seems uncertain. The information available concerning these wells is meager and unsatisfactory, but it seems that the alluvium of the valley—much of it fine, clay-like soil—plays the rôle of an impervious layer and retains water under pressure in the seams and joints of the basalt, thus furnishing an approach to favorable artesian conditions.[1]

Wells at Palouse.—Four wells have been drilled within a radius of

[1] It is probable that if these wells were properly cased a surface flow would result.

about 20 feet in the business portion of Palouse, with the hope of obtaining a water supply for the town. The last was completed in 1894. The town is situated principally in a valley with precipitous borders 280 feet high. The wells are in the bottom of the valley, and are said to be about 200 feet deep and to penetrate material as follows:

	Feet.
Earth and stones	14
Coarse gravel	3
Solid basalt	100
Coarse sand	9
"Black slate rock"	30
Sand, water-bearing	25 to 30

Of these four wells, the first drilled is now closed, and the remaining three discharge collectively about 10 gallons per minute. The wells are 8 inches in diameter at the top, but are said to decrease to 6 inches, and again to 2 inches toward the bottom.

The wells are a failure so far as supplying the town is concerned, but it is evident that if casings could be introduced their efficiency would be increased.

Well at Garfield.—A well has been drilled at Garfield with the hope of obtaining artesian water for the town, but did not meet with success. The well is reported to have been drilled to a depth of about 300 feet with a 6-inch bit, and afterwards enlarged by excavating to 8 feet to a depth of 100 feet. From this well water is now pumped for the supply of the town. The excavated portion of the well passed through earth and bowlders; apparently the upper part of this material is a stream deposit and the lower portion disintegrated basalt. Below the open well the drill passed through "honeycomb" rock; by this is probably meant much-jointed and possibly scoriaceous basalt.

James Walter's well.—Three miles northeast of Garfield, at the residence of Mr. James Walter, a drilled well 113 feet deep was completed in 1892. This is a flowing well, and discharges a stream of water 1¼ inches in diameter. The section passed through is reported by Mr. Walter as follows:

	Feet.
Dirt	16
Basalt	65
Blue clay	5 to 6
Gray clay	5 to 6
Hard cement	2
Blue and yellow clay, with quicksand, water-bearing	10 to 12

The surface of the ground at the locality where this well was drilled is reported to be higher than Garfield, but no measure of its elevation is available.

Other wells.—Incomplete reports have been obtained of not fewer than a score of wells, in addition to those mentioned above, in a belt of country about 15 miles wide, extending northward from near Snake

River, along the eastern border of Washington. The time available for making a personal examination of this region was so limited that little more than the facts here reported could be obtained.

The success which has followed a large number of the attempts already made to obtain artesian water in this region, and the facts learned concerning the nature and relations of the rocks, certainly indicate that artesian water can be had at a moderate depth over a wide extent of rich agricultural land.

The western border of the region in which artesian water can be had is indefinite. The region to the west of a north-and-south line passing through Garfield, including the greater part of Whitman County and all of Adams and Franklin counties, is geologically unknown, except so far as the conditions there prevailing can be judged from what has been seen in adjacent areas. Whether test wells have been put down in this region or not I have failed to learn.

There is no definite evidence in hand to show that the sands and clays penetrated at Pullman, Garfield, etc., extend far westward, but it is reasonable to suppose that such is the case. It is probable also that layers of clay and sand exist lower in the series than those penetrated at Pullman, which may furnish similar conditions in the region to the west.

Besides the presence or absence of pervious and impervious layers, the dip of the beds and the depth to which they have been dissected by streams have also to be considered. While there seems a probability that artesian wells may be had over a wide extent of country to the west of the region at present explored, lack of definite information concerning that region makes it impossible for one to form an opinion in this connection.

ARTESIAN CONDITIONS SOUTH OF SNAKE RIVER.

The question of obtaining artesian wells in that portion of Washington which lies south of Snake River resolves itself into two considerations with reference to source of supply: First, can water be had under conditions similar to those existing at Pullman from strata leading westward from the mountains of Idaho? Second, are there water-bearing strata dipping away from the Blue Mountains?

With reference to the first of these questions, it is to be remembered that Snake River Canyon cuts off all possible sources of supply to a minimum depth of about 2,000 feet below the general surface of the basaltic plateau. We have only indefinite evidence as to the nature of the rocks below the level of Snake River. As the basaltic layers exposed in the canyon of that river are nearly horizontal, it is evident that the artesian head for any porous layers which may exist below the horizon of the river would be low. The manner in which the series of horizontally bedded basaltic sheets abuts against the metamorphic rocks on the east renders it extremely improbable that

any deeply seated porous stratum could be water-charged in such a manner as to make it a source of artesian water.

The considerations just indicated are of such weight that there seems no need of hesitation in declaring it useless to hope for success in drilling wells in the region south of Snake River with the view of obtaining water from sources similar to those which supply the wells in the neighborhood of Pullman.

Turning to the second possible source of artesian water suggested, namely, the Blue Mountains, we find that the rocks dip away from that uplift, and also that they are abundantly water-charged. Two of the primary conditions requisite for obtaining subterranean water under pressure are thus fulfilled. Inquiries in at least two other directions must be made, however, before a conclusion can be reached. These are: First, are there layers of clay and sand interbedded with the basalt? and second, have the rocks been so deeply dissected by streams as to allow pervious beds, if they exist, to be drained?

Beds of clay and of fragments of volcanic rock (lapilli and volcanic dust) interbedded with basalt occur in the neighborhood of Asotin, and possibly extend southwestward and westward, but no exposures of these layers were seen by me in the Blue Mountains. My examination, however, was not sufficiently detailed to prove that they are there absent.

The material forming the clay beds referred to was derived from the mountains of Idaho before the cutting of Snake River Canyon, and probably thin out westward. No layers of sand like the one yielding water at Pullman are known to occur beneath the clays, and the strata of lapilli and volcanic dust are not sufficiently porous to be classed as water-bearing strata. It is thus exceedingly doubtful if the succession of beds in the flanks of the Blue Mountains affords the arrangement of pervious and impervious layers necessary for an artesian water supply.

With reference to the depth to which the rocks forming the Blue Mountains and the plateau extending northward from them have been dissected by streams, it will be remembered that deep erosion has occurred. In the mountains there is a veritable labyrinth of canyons from 2,000 to 3,000 feet deep. This deep erosion, however, is favorable to the process of charging with water any pervious layer that may exist in the flanks of the range, since the edges of the layers are exposed to the rain and to water flowing down the sides of the canyons or percolating through the soil that mantles the cut edges of the strata.

The canyons leading northward from the Blue Mountains soon increase in depth, and the plateau in the northern portions of Garfield and Columbia counties is deeply dissected. Evidently any porous strata that are cut by these canyons could not contain water under pressure. The only possible hope for obtaining artesian water in the counties just mentioned is, therefore, below the level of the canyon

bottoms. The expense of drilling wells from 500 to 2,000 feet deep through basalt, as would of necessity be the case on the fragments of the plateau remaining between the streams, even if success at these depths were assured, would preclude the use of water thus obtained for irrigation.

In the canyons there is a chance that artesian water might be reached, but the conditions are so uncertain that the experiment of sinking wells below a depth of 100 or 200 feet should not be made, except as a last resort. The more practical and entirely feasible method of utilizing the surface streams within the canyons makes it unwise to incur expense in the search for subterranean water. The possibility of obtaining water from the alluvium of the canyons will be referred to later.

In the valley of the Walla Walla, in a general way westward of a line connecting the cities of Walla Walla and Milton, Oregon, there is an absence of canyons. In this region, also, there is at least one clay stratum interbedded with the basalt, but no evidence of the presence of layers of sand has been obtained. This is the only region in Washington south of Snake River where the hasty examination I have been able to make suggests the possibility of obtaining artesian water at reasonable expense and where there are lands available for farming. Even in this region the certain method of utilizing the abundant surface water is much to be preferred to the uncertainty of attempting to obtain flowing wells. The geological conditions in the valley of the Walla Walla are not such as to warrant the prediction that success would follow the drilling of a well, but simply that there is a possibility of success. The best locality for drilling a test well in this region is in the vicinity of Whitman. A trial made at Walla Walla would probably be equally decisive. At Whitman a depth of 150 to 200 feet of surface material would probably have to be passed through before rock in place would be reached, but in this upper portion of the section flowing water is likely to be met. At Walla Walla the superficial material—the bowlder and gravel of Mill Creek—is apparently not deep and might also yield flowing water.

In order to test the possibility of obtaining water at Walla Walla I should favor the project, already proposed, of drilling a well at the State penitentiary. To make the test conclusive, the proposed well should be drilled to a depth of 500 feet, if flowing water is not obtained nearer the surface.

WELLS IN ALLUVIUM.

There are flowing wells of another class that require mention, but which are scarcely to be classed with true artesian wells.

The deposits made in stream channels and over flood plains are usually composed of irregular layers of bowlder, gravel, sand, clay, etc., through which the stream waters percolate. The water in the pervious layers is sometimes under moderate pressure and will rise

to the surface when wells are dug. The pervious beds are usually irregular and of small extent, and their water supply, being furnished by the stream which deposited them, varies with changes in the volume of the stream. No one can tell, without making practical test, whether the percolating waters in an alluvium-filled valley will rise to the surface or not. The best way to search for such waters, where the alluvium does not contain large bowlders, is by driving pipes into the ground. Where bowlders 1 foot to 2 or 3 feet in diameter are met with, driven wells are impracticable. It is also difficult and expensive to drill through deposits of bowlders, so that the only practicable method seems to be to make the excavation by hand. In some instances, when a strong flow of water is reached, if the bottom of the well is covered with cement, through which a pipe is inserted leading to the surface, a surface flow may be obtained.

As is well known, the bottom of many of the canyons leading from the Blue Mountains are deeply filled with alluvium, in which water may be obtained. An excellent method of conducting the percolating water of alluvial deposits to the surface and making them available for use lower down the valley in which they occur, without pumping, is in operation at Walla Walla.

WATERWORKS AT WALLA WALLA.

Walla Walla is now supplied with water from infiltration ditches prepared in the coarse gravel that forms the flood plain of Mill Creek, about a mile above the central part of the town. The water from the infiltration ditches is conducted into reservoirs, from which it is distributed by gravity. The fall of Mill Creek in the vicinity of Walla Walla is 63 feet per mile. This rapid descent makes it possible to locate reservoirs near the town. The infiltration ditches are dug as open ditches to a depth of from 12 to 15 feet. At the bottom an inverted trough made of planks is placed and covered with clean gravel to the depth of several inches. The gravel also fills the space between the sides of the inverted trough and the undisturbed material forming the walls of the ditch. The material removed in digging the ditch is then replaced. The use of tiles in place of the inverted wooden trough would have advantages, but would be more expensive.

The infiltration ditches are located at angles of 30° to 40° with the direction of slope, and trend upstream. The water percolating through the gravel enters the inverted troughs from below and also flows through the loose gravel covering them, and is conducted to reservoirs. The length of the infiltration ditches varies. As an example of their efficiency I insert the following information, furnished by the superintendent of the waterworks, concerning what is termed "Reservoir No. 2." This reservoir is a tank excavated in the gravel, but not lined, and sheltered by a timber and shingle roof. It is rectangular, measures 51 by 90 feet on the sides, and is 10 feet

deep. Two infiltration ditches lead to this tank, one 500 and the other 800 feet long. These discharge during the summer season about 320,000 and 420,000 gallons, respectively, per day.

There are two other reservoirs of similar dimensions, supplied in like manner. The water reaching the reservoir is thoroughly filtered, and at present, as shown by sanitary analyses, is wholesome and of an agreeable temperature.

This method of obtaining a water supply is recommended for its economy, and on a smaller scale might be advisable in many instances for farm purposes, in place of wells now commonly in use. The advantages over surface wells are that the water supply may be drawn from a distance from sources of contamination, and when properly arranged the trouble and expense of pumping are avoided.

The only objection that can be suggested to this method of supplying towns or residences with water is that it comes from superficial deposits and is in danger of contamination from houses, stables, etc., situated upstream from where the infiltration ditches are located. In countries of small rainfall, where the streams are greatly lowered during the summer, the dangers from these sources are multiplied. For 9 or 10 miles above Walla Walla the narrow canyon-like valley of Mill Creek is occupied somewhat thickly by farmhouses and stables. Contamination of the city water supply from these sources is a constant menace.

CONCLUSIONS.

The results of the hasty examination of the geology of southeastern Washington here reported on, so far as the question of artesian water is concerned, may be briefly summed up as follows: In the Palouse country there are reasons for believing that the area in which artesian water has been found will be broadened westward. South of Snake River there is no evidence that success would accompany the drilling of wells on the uplands. In the canyon bottoms there is a possibility of finding artesian water, but further than this the study of the geology does not offer suggestions, except of an adverse character. The chances of failure far outbalance the chances of success. To the northwest and west of the Blue Mountains—more definitely, in the valley of the Walla Walla westward from a line joining the towns Walla Walla and Milton, and possibly extending some distance into Oregon—the conditions are more favorable than elsewhere in Washington south of Snake River and warrant the drilling of a test well should the demand for water be great. Even in this most favorable area, however, I should recommend the full utilization of the streams and the storage of the winter run-off before attempting to obtain artesian water for irrigation purposes.

AN OUTLINE SKETCH OF THE GEOLOGICAL HISTORY OF SOUTHEASTERN WASHINGTON.

Of the ancient geological history of Washington but little is known. The northern portion of the Cascade Mountains, as shown recently by Bailey Willis, is largely composed of metamorphic rocks. Similar rocks occur about Lake Chelan and north of the Big Bend of the Columbia and of the lower portion of Spokane River. From Spokane the hills formed of these metamorphic rocks extend southward along the Washington-Idaho boundary, and from them the mountains of western Idaho have been sculptured.

The rocks just referred to as being of metamorphic character—that is, greatly changed by heat and heated solutions from their original condition—were in many instances of sedimentary origin, but are now granite, schist, quartzite, etc. The granites, however, may be in part of igneous origin—that is, were once in a molten condition—but of this no direct evidence has been observed. The place in the earth's history where these rocks belong is unknown, but their crystalline condition suggests that they are very old, and possibly belong to the series termed Archean. The resemblance of metamorphic rocks in one region to similar rocks at a distance is an uncertain basis for classification, however, for the reason that strata belonging to widely different periods, when changed by heat and heated water, produce granites, schists, etc., having the same characteristics. Some of the granites of the Pacific Coast are known to be of comparatively recent geological date.

The structure of the rocks of the metamorphic regions of Washington—that is, the positions which the rocks occupy, whether folded, contorted, broken, etc.—is not well known, although it is easily seen that those which still retain evidence of bedding, and were without question originally in horizontal sheets, have been upturned and bent into great folds. Throughout the metamorphic region the country is mountainous, and much of the geological history of the region is recorded in their forms. The valleys have been carved out of the upraised mountain masses, and each dome and crest has been slowly fashioned by rain, frost, wind, and rills into its present transient shape. The depth to which the valleys have been excavated and the forms of the bordering hills show that the mountains are old and have formed a land surface for geological ages.

In comparatively recent geological times the mountains of northern Washington and eastern Idaho, although probably higher and more rugged than now, had their present general outlines, but the central and southern portions of the Cascades, as well as the Coast Range, were as yet unborn. The country south of the southward-facing semicircle of mountains, embracing the present great plain of the Columbia and southeastern Washington, was low and partially submerged at times beneath the sea. This vast low-lying area,

together with the surrounding mountains, was clothed with varied and beautiful forests, resembling those of the South Atlantic States at the present day. In this valley region, which extended far south, there were lakes and swamps in which vegetable matter accumulated and was later changed to coal. Some of this coal is now mined at Roslyn. The luxuriant vegetation, a part of which has been preserved as coal, furnished food and shelter for a variety of animals, no near relatives of which are living at the present day.

This age, when almost subtropical conditions prevailed, was in the early Tertiary. As time passed, the lakes became filled with sediment, and much of the region sank beneath the sea. Clays and sands were spread out which have since hardened into rock. Upheaval brought these once level sheets of rock above the sea and raised them into a mountain range—the southern Cascade. In central Washington these early Tertiary rocks were eroded, and outbreaks of volcanic energy caused lava sheets to be spread over them. Fissures opened in the earth's crust, and molten rock was poured forth in such wondrous abundance that thousands of square miles of valley lands were inundated by the fiery floods. The lavas were similar to those poured out within the past few years by the volcanoes of the Hawaiian Islands and other regions. The molten rock was highly liquid, flowed rapidly, and spread out in sheets of broad extent. On cooling, it formed the dense, black basalt now so familiar throughout central and southeastern Washington. This is the Columbia lava, so frequently mentioned on the preceding pages.

Vast outwellings of molten rock occurred at intervals throughout a period embracing many hundreds and probably many thousands of years. The time between successive flows was sufficiently long, in numerous instances, to allow the surface of the cooled and hardened lava to crumble and decay under the action of the atmosphere and form soils on which forests of oak and pine took root and flourished. In some instances abundant showers of volcanic dust, similar in character to the fine dust-like material blown out by many volcanoes in historic times, covered the land and buried the still erect trees. Later lava sheets were spread over the entombed forests, and in some localities charred the trees and changed them to charcoal. When the trees were so protected by their covering of volcanic dust that they were not directly influenced by the heat of the lava that flowed over them, heated waters brought silica to them in solution, and they were changed to stone. The stumps of these silicified or fossilized trees, still standing as they grew, may be seen in the sides of the canyons that streams have cut in the thick pile of lava sheets. The replacement of the wood in these buried forests by silica, usually in the form known as opal, was so complete that not only the grain of the wood but each duct and cell is preserved, and when examined in thin sections under the microscope it appears as perfect as the wood of a living tree.

Lava flow succeeded lava flow until the vast valley region embraced

in part by the mountains of northern Washington and eastern Idaho, thousands of square miles in extent, was covered with basalt to an average depth of probably 3,000 or 4,000 feet. The molten rock spread widely over the lowlands and about the bases of the bordering mountains and extended up the tributary valley. As sheet after sheet was added the hills in the lowlands became buried; outstanding spurs of the mountains became capes in the sea of molten rock; isolated mountain peaks were surrounded by the fiery flood and submerged, or left as islands rising above its surface.

This vast inundation of lava is one of the most remarkable and, I may say, one of the most dramatic incidents in the geological history of North America. It is safe to assume that all the lava poured out by volcanoes within historic times, if run together, would make but a small fraction of the mass under which the region drained by the Columbia is buried.

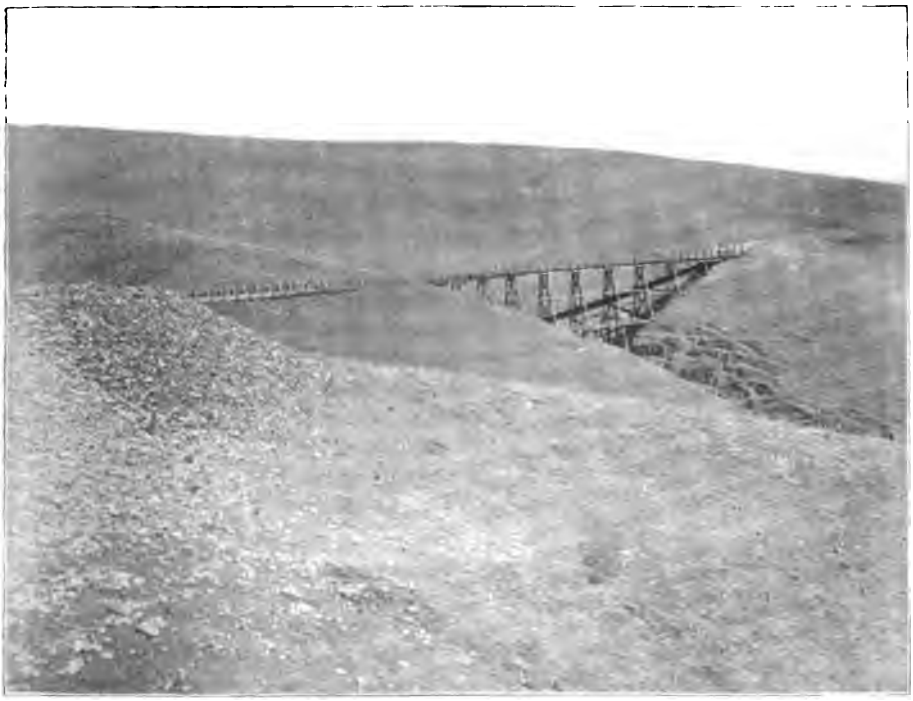
During the lava flows streams from the bordering mountains met the encroaching sheets of molten rock, and many grand spectacles of conflict between water and fire might have been witnessed, but of the presence of man on this continent at the time of these vast eruptions we have no records. Some of the sheets of volcanic fragments interbedded with the lava sheets appear to have been formed by the shattering and rapid cooling of the highly heated rocks on coming in contact with water.

Layers of fine, pure-white volcanic dust between the sheets of basalt show that distant volcanoes were in a state of violent eruption at the time these deposits were made, and the wind carried the dust far and wide over the land. That the dust did not come from the same eruptions that supplied the basalt is shown by marked differences in chemical and mineralogical composition. The dust is an acid rock—that is, rich in silica—while the basalt is basic.

During the intervals between the lava flows lakes were formed on the surface of the cooled basalt and sheets of sediment were laid down. These lakes came into existence, especially about the borders of the lava-covered country, for the reason, in central and eastern Washington at least, that the advance of the lava was toward the mountains, and on cooling formed land surfaces which sloped gently toward the uplands and intercepted their streams. In some instances the lava flowed far up the valleys and gave them a nearly level floor of solid basalt. Sand and gravel, swept out of the mountains by swift-flowing streams, was spread over the lava during intervals between the fiery floods. Alternating sheets of basalt, sand, and clay were thus formed, especially about the borders of the lava-covered region, and furnished the requisite conditions for storing water under pressure. Artesian wells ages later were thus made possible.

Toward the close of the long period during which the lava sheets were spread over the lowlands the lakes formed on their surface

LEWISTON IRRIGATION CANAL.



FLUME IN LEWISTON IRRIGATION CANAL.

became of broad extent, but were invaded from time to time by additional layers of volcanic rock, which were buried by still younger lacustral deposits. At length the volcanic energy ceased and deep and widely extended lacustral sediments were accumulated. The broad lakes in which these sediments were laid down in even layers were probably held in basins formed by the upheaval of the Cascade Mountains. The light-colored and evenly bedded deposits referred to may now be seen at the White Bluff of the Columbia, in Wenas and Natches valleys in Washington, and in John Day Valley in Oregon. Leaves of many kinds of trees and the bones of mammals occur in these deposits and record the fact that after the vast outpourings of lava came to an end the land was again forest covered and inhabited by many large animals, all of which are now extinct. Thick layers of volcanic dust interleaved with the lacustral clays and sands bear evidence of violent eruption in distant volcanoes.

With the drainage of the lakes that covered large portions of the lava country with sands and clays, the streams from the mountains flowed to the sea, and were enabled to carve canyons in the hard lavas. At an early stage in this epoch stream-borne gravels were carried out onto the basaltic plateau, and the most resistant of the stones thus deposited—the hard quartzite—may still be found in many places on the general plateau surface between deep canyons.

Snake River slowly carved out its channel until, at the present time, in the eastern flank of the Blue Mountain uplift it is an immense gorge some 15 miles broad at the top and about 4,000 feet deep. The work of stream cutting is slow. If we could study Snake River for a century where it flows over hard basalt, it would be difficult to determine the depth—probably not over a fraction of an inch—that it had lowered its bed. The river performs this task mainly by abrasion. Stones and sand swept along by the current wear the rocks over which they pass. Basalt is dense and hard, and, although decomposing with comparative rapidity when exposed to the air, yields very slowly to mechanical wear. The task of cutting to its present depth the magnificent canyon which now excites the wonder and admiration of all who behold it must have required an almost infinite time, as it appears to us. This task has been performed, however, since the lava sheets were spread out over southeastern Washington, and for the most part since the lake beds containing the records of extinct floras and faunas resting on the lava were laid down.

There are reasons for believing that the canyon of Snake River was excavated to its present depth before the time in the earth's history known as the Glacial epoch. Space will not permit of a review of all the facts that lead to this conclusion, but a great gravel terrace in the canyon of Snake River and similar terraces in the canyons of Columbia and Spokane rivers show that after they were worn to their present depth they were filled to a height of 300 or 400 feet—360 feet in the case of the Snake River below Lewiston. This filling is attributed

to the overloading of the streams with débris furnished by glaciers and by swollen mountain streams. The cause of this change was climatic. During the Glacial epoch Washington and Idaho, in common with the northern half of the continent, had a colder and more humid climate than now. The streams flowing from the mountains were thus enlarged, and more earth and stones were swept into the channels of the main streams than they could transport.

The great climatic change which caused about one-half of the North American Continent to be covered with glacial ice left no records in southeastern Washington except those briefly referred to. Glaciers existed on the mountains of Idaho and Washington, but did not invade that portion of the basaltic plateau now included within the boundaries of Washington except locally at the northwest border of the Big Bend country. This advance of ice from the Okanogan country across the canyon of the Columbia dammed that mighty river and caused it to flow across the great plain of the Columbia, through the remarkable gorge known as the Grand Coulée.

Since the Glacial epoch the streams have shrunk in volume, owing to the combined effects of a decrease in precipitation and an increase in the rate of evaporation, and in their weakened condition they have scarcely done more than recut their channels through the gravel and sand previously deposited in them.

The vast amount of work performed by Snake River previous to the Glacial epoch, the halt in the task due to overloading, and the slow rate at which the weakened stream has been able to renew its task in recent centuries, all indicate that the time required for excavating the canyon has been long. We have no accurate measure of this time, but it is safe to say that it embraced millions of years.

The sheets of Columbia lava were essentially horizontal when they were spread out, and, so far as known, they were not disturbed until after the volcanic eruptions, to which they are due, came to an end. Movements in the earth's crust occurred at a later date, however, and the thick series of basaltic layers were broken into blocks measuring many miles on their sides, and these were variously tilted. This breaking and tilting occurred principally to the westward. Some of the tilted blocks extend far up on the eastern border of the Cascade Mountains, showing that the central and southern portions of that magnificent range have been upraised since the period when the Columbia lava was poured out.

In southeastern Washington the basalt has suffered but little from the forces producing elevations and depressions, and over extensive areas the hardened lava is still horizontal. The portion of the lava forming the Blue Mountains has been elevated into a broad, low, flat-topped dome, on the flanks of which, so far as has been learned, the beds of basalt dip away gently in all directions. The movements that have produced these more general changes in the relief of the basalt-

covered country are probably still in progress, as is indicated by the manner in which Walla Walla River is grading up its valley at the western base of the Blue Mountains.

The surface of the basaltic plateau, which is by far the larger part of southeastern Washington, as already stated, remained nearly horizontal, and during the vast lapse of time that witnessed the excavation of Snake River Canyon slowly yielded to the destructive influences of the air and of percolating waters and crumbled to a porous soil. The depth of the products of disintegration and decay is in many places 60 to 80 feet. In fact, over hundreds of square miles the average depth of the fine, yellowish, dust-like material forming the surface layer of rich agricultural districts is as great as the amount just stated.

The surface of the nearly level plateau has been roughened by stream erosion, but its plateau character not destroyed. Numerous level-floored valleys without stream channels bear evidence that the rainfall was formerly more abundant than now. The stream-cut canyons and valleys have been partially filled with fine soil, washed from the adjacent hills or blown from the uplands by the wind. The minor topographic features of the plateau, although due in the main to stream erosion, have been modified to an appreciable and sometimes to a marked extent by the action of the wind.

It is from the soil formed by the slow disintegration and decay of basaltic rocks that the millions of bushels of wheat raised each year in eastern Washington are obtained. The sending of wheat from the State of Washington to the famishing people of India, which has recently been done, is rendered possible because ages ago volcanic rocks capable of furnishing a wonderfully rich soil inundated the Tertiary lowlands where now "rolls the Oregon." The splendid water power at Spokane and the marvelous growth of that charming city can be traced to a climatic change which caused the valley in which it is situated to become deeply filled with stream deposited gravel. When the bright, swift-flowing waters were enabled to clear out their channel, they did not rediscover their former course at all points, but cut across rocky spurs projecting from the sides of the old valley. One such occurrence gave Spokane its beautiful cascade. Many other illustrations of the influence of events in the geological and geographical history of Washington which bear directly on the industrial and intellectual development of the present generation might be cited.

In closing this report of a hasty reconnoissance, I wish to state that the studies thus far made of the geology of Washington show that it is not only one of the most interesting States in the Union to the geologist and geographer, but that it is also rich in mineral and other resources.

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DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 5

IRRIGATION PRACTICE ON THE GREAT PLAINS.—Cowgill

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

IRRIGATION REPORTS.

The following list contains the titles and brief descriptions of the principal reports relating to water supply and irrigation prepared by the United States Geological Survey since 1890:

1890.

First Annual Report of the United States Irrigation Survey, 1890, octavo, 123 pp.

Printed as Part II, Irrigation, of the Tenth Annual Report of the United States Geological Survey, 1888-89. Contains a statement of the origin of the Irrigation Survey, a preliminary report on the organization and prosecution of the survey of the arid lands for purposes of irrigation, and report of work done during 1890.

1891.

Second Annual Report of the United States Irrigation Survey, 1891, octavo, 336 pp.

Published as Part II, Irrigation, of the Eleventh Annual Report of the United States Geological Survey, 1889-90. Contains a description of the hydrography of the arid region and of the engineering operations carried on by the Irrigation Survey during 1890, also the statement of the Director of the Survey to the House Committee on Irrigation, and other papers, including a bibliography of irrigation literature. Illustrated by 29 plates and 4 figures.

Third Annual Report of the United States Irrigation Survey, 1891, octavo, 576 pp.

Printed as Part II of the Twelfth Annual Report of the United States Geological Survey, 1890-91. Contains a report upon the location and survey of reservoir sites during the fiscal year ending June 30, 1891, by A. H. Thompson; "Hydrography of the arid regions," by F. H. Newell; "Irrigation in India," by Herbert M. Wilson. Illustrated by 93 plates and 109 figures.

Bulletins of the Eleventh Census of the United States upon irrigation, prepared by F. H. Newell, quarto.

No. 35, Irrigation in Arizona; No. 60, Irrigation in New Mexico; No. 85, Irrigation in Utah; No. 107, Irrigation in Wyoming; No. 153, Irrigation in Montana; No. 157, Irrigation in Idaho; No. 163, Irrigation in Nevada; No. 178, Irrigation in Oregon; No. 193, Artesian wells for irrigation; No. 198, Irrigation in Washington.

1892.

Irrigation of western United States, by F. H. Newell; extra census bulletin No. 23, September 9, 1892, quarto, 22 pp.

Contains tabulations showing the total number, average size, etc., of irrigated holdings, the total area and average size of irrigated farms in the subhumid regions, the percentage of number of farms irrigated, character of crops, value of irrigated lands, the average cost of irrigation, the investment and profits, together with a résumé of the water supply and a description of irrigation by artesian wells. Illustrated by colored maps showing the location and relative extent of the irrigated areas.

1893.

Thirteenth Annual Report of the United States Geological Survey, 1891-92, Part III, Irrigation, 1893, octavo, 486 pp.

Consists of three papers: Water supply for irrigation, by F. H. Newell; American engineering and engineering results of the Irrigation Survey, by Herbert M. Wilson; Construction of topographic maps and selection and survey of reservoir sites, by A. H. Thompson. Illustrated by 77 plates and 119 figures.

A geological reconnoissance in central Washington, by Israel Cook Russell, 1893, octavo, 108 pp., 15 plates. Bulletin No. 108 of the United States Geological Survey; price, 15 cents.

Contains a description of the examination of the geologic structure in and adjacent to the drainage basin of Yakima River and the great plains of the Columbia to the east of this area, with special reference to the occurrence of artesian waters.

(Continued on third page of cover.)

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UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

IRRIGATION PRACTICE ON THE GREAT PLAINS

BY

ELIAS BRANSON COWGILL

WASHINGTON

GOVERNMENT PRINTING OFFICE

1897

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, March 3, 1897.

SIR: I have the honor to transmit herewith a paper entitled "Irrigation Practice on the Great Plains," by Prof. E. B. Cowgill, and to recommend that it be published in the series of papers upon water supply and irrigation. Professor Cowgill's experience as a practical farmer and irrigator and as the editor of an agricultural paper renders his observations upon irrigation practice of especial value in discussions of the methods of utilizing the water resources of semiarid areas.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

IRRIGATION PRACTICE ON THE GREAT PLAINS.

By E. B. Cowgill.

GENERAL STATEMENT.

The characteristics of topography and climate which influence the practice of irrigation on the Great Plains may be summed up in the general statement that the land is usually smooth, the soil extremely deep and fertile, the rainfall scanty and irregular, the sunshine abundant, and the water supply variable and uncertain. In seasons of unusual rainfall a stranger entering western Kansas is astonished that a land of such remarkable productiveness has been almost abandoned since its first settlement. Coming again after a season of deficient rainfall he would be equally surprised that anyone could have been tempted to try to make a living on the barren prairies. Happening upon a spot where irrigation is practiced, he at once appreciates the enormous importance that water bears to the successful settlement of the country, for there agriculture on a small scale is profitable no matter what may be the character of the season; there all of the elements—soil, sunshine, and water—combine to produce a fruitful increase of plant life.

The water supply of the region, at best scanty, is yet ample for the development of considerable areas, far greater than are at present occupied. In this paper it is not proposed to discuss what or where these sources are, but, assuming that water is to be had from surface streams, storm waters, or wells or other underground sources, the attempt is made to describe in a general way to the farmers, especially to those who have not practiced irrigation, the methods of controlling, storing, distributing, and applying the waters to the cultivated fields. It is recognized that no description can ever take the place of actual experience, but it is possible to give general directions which the individual farmer, by experiment and observation, can adapt to his peculiar needs.

RESERVOIRS FOR STORM WATERS.

Artificial reservoirs have been found a necessity in the irrigation of the plains. Storm waters can not be controlled or directed upon the land as they fall. They run off from the hard, sun-baked prairies in torrents, especially in those portions of the country where reliance must be placed chiefly on such waters. For the storage of this water reservoir sites are easily found, and are usually selected with a view to impounding the water from a considerable drainage area. The retaining dams are of various sizes, according to the needs and the means of the persons constructing them. A reservoir to contain an acre or so of water is easily made by placing an earthen dam across the outlet of the drainage area, even though the slopes may be very gradual. The dam has not usually to be built very high, and the principal precaution necessary is to provide against washing out in time of freshet. The larger reservoirs differ in no essential from the smaller, except that the sites must be selected with reference to larger areas of drainage, and the dams usually require more work, both as to engineering and construction.

A typical example of this kind is the reservoir of George M. Munger, of Greenwood County, Kansas. Mr. Munger is engaged extensively in orcharding, having 500 acres of fruit trees ready to bear. Notwithstanding his location near the ninety-sixth meridian, far within what is usually designated as the "rain belt," he has concluded, after careful investigation of the subject, that the realization of the expected profits of his orchard is dependent to a large extent upon the artificial application of water. There are no surface streams near from which to obtain water in the usual way. There is on his farm, however, an eligible site for a storm-water reservoir. But most of his orchard and farming land is at a higher level than the reservoir site, so that, after collecting the water, he is obliged to pump it.

The accompanying view, Pl. I, gives the relative location of the orchard and source of water supply. The storm reservoir can be seen in the distance to the left, while between it and the orchard is the pumping station. The ravine in which the dam is placed runs diagonally through the farm. The sides of it have a gentle slope, thus necessitating the construction of a dam of considerable length, as shown in the illustration, Pl. II. In order to provide a safe and sufficient spillway, it was necessary to build the dam to considerably larger dimensions than would otherwise have been essential. The topography is such that water could be wasted over a natural ridge having a breadth of about 1,000 feet. It was therefore decided to carry the dam to a sufficient height above this ridge to hold in check any freshet of unusual size and turn it over the crest of this depression.

The watershed above the point at which the dam is located is about 800 acres in extent. The valley shows by watermarks that the high

MUNGER ORCHARD, GREENWOOD COUNTY, KANSAS.

Part of a 500-acre orchard irrigated with storm water.

floods spread out to the width of about 300 feet. The dam is 2,582 feet long, 192 feet broad at the widest part of the base, and a little less than 40 feet at the highest point above the bottom of the valley. The estimated area of water when full is 160 acres, and the estimated capacity 1,600 acre-feet.[1] It was expected that two years of average run-off would fill the reservoir.

In the construction of the dam, which was built exclusively of earth, the sod was entirely removed and placed at the rear face. The old water channel was thoroughly cleansed of the washed-in gravel, and the work begun with new earth. The soil is a heavy clay with the usual variations, including probably a full supply of gumbo and alkali.

The matter of seepage through the dam and the method of correcting it was considered by Mr. Munger, who states in general terms that while the authorities on the construction of earthen dams recommend that the earth be especially selected for the face, and a puddle trench be placed in the heart of the work, it seemed difficult to formulate a scheme for so doing that did not involve too great expense. Earth was taken as it came in the borrow pits, and in each successive pit was used as deep as it could readily be obtained. All earth was taken from inside the work, except where it could not be had without too great a haul. Several smaller dams had been previously constructed on the place, and in each and every place there was a seepage along the toe of the dam, but in no case was it sufficient to endanger the stability of the work. The same trouble developed in this work, and on account of the magnitude of the dam it was deemed expedient to correct it. This was accomplished by running a permanent stone drain along the toe of the dam, grading it to the lowest point possible, and running laterals to every seepy spot that showed. The result was very satisfactory, there having been a small stream running from the drain constantly since its construction, but now materially reduced in volume.

The original estimate shows about 100,000 cubic yards as the earth contents of the dam, but, on account of the action of the waves on the surface of the dam, it was found that the estimate was considerably exceeded. It was found impracticable to prevent, by riprapping, the water from bringing the face of the dam to the natural grade, so that no protection had been provided against the action of the waves until the grade determined by the water was made, when the face of the dam was riprapped to prevent further loss of earth from the action of the waves.

Except for the fact that Mr. Munger has many hundreds of acres of land to irrigate, so large a construction would not be advisable, but the plan of this reservoir and the methods pursued in its construction

[1] Irrigating a 500-acre orchard, by George M. Munger: Report of the Kansas State Board of Agriculture for the quarter ending March 31, 1895, pp. 66–71.

may well be taken as models by those whose requirements demand reservoirs of only moderate size. Water may be drawn through a flume for the irrigation of considerable areas of Mr. Munger's farm which lie at a lower level than that of the water in the reservoir, but for most of the farm it is necessary to raise water. This is done by two compound, duplex, direct-acting steam pumps of a daily capacity of about 4,000,000 gallons, which forward the water rapidly enough to make unnecessary a distributing reservoir from which to draw the water when supplying it to the land.

RESERVOIRS FOR PUMPED WATER.

Reservoirs for pumped water differ in several respects from those for storm water. The site for a pumped-water reservoir should be selected on the highest part of the land to be irrigated. The form will not usually be determined by the contour of the land, but by the taste or convenience of the irrigator. Not infrequently such reservoirs are made square, or at least rectangular. Some are made circular, thus securing the greatest content for a given amount of embankment. In size, pumped-water reservoirs vary from quite small, as shown by Pl. III—say 30 feet square—to those containing half an acre or an acre of ground. Irrigation with pumped water has been confined to small operations, at least in Kansas and upon the Great Plains, making large storage capacity unnecessary. Since pumping into the reservoir is done almost exclusively with windmills, the work of which varies with the wind, it is sometimes thought that the size of reservoir, compared with the land irrigated, should be considerably increased above the dimensions now in common use. But the practice has been to use the reservoir as an accumulator, giving the irrigator command of his water supply rapidly, rather than as a store against the time when water may not be obtained by the aid of the wind. Experience has confirmed the practice of using the reservoir merely as an accumulator, except for large gardening operations, for which a delay in the application of water sometimes proves disastrous. With other crops it is found quite possible to anticipate probable scarcity by storing abundance of moisture in the porous subsoil. The relative size of the reservoir to the land to be irrigated averages from about 1 to 80 to about 1 to 100.

The depth of the reservoir when first constructed is generally 4 feet; that is, the bank which constitutes the dam all around the area to be filled with water is raised about 4 feet above the natural surface of the soil, as shown in fig. 1. The earth for the construction of the dam is usually taken from within the reservoir, so that the depth of water in the reservoir would be somewhat more than 4 feet if it were filled to the top of the bank.

SMALL IRRIGATION RESERVOIR, AT GARDEN, KANSAS.

Reservoirs are, as a rule, made on land which has been under cultivation. In preparing for the work all trash should be removed and the ground which is to serve as the foundation of the dam should be about four times as broad as the height of the proposed embankment around the reservoir. It is a good plan in plowing this foundation to turn the furrows so as to leave a dead furrow in the middle and then to pump water into this dead furrow, wetting all the base of the dam

FIG. 1.—Reservoir and windmill north of Garden, Kansas.

thoroughly. After this has sufficiently settled to admit of driving over it, it is well to tramp it by driving horses or other heavy animals over it until it is well compacted. The land in the interior of the reservoir is plowed and the loose earth is removed to the embankment, usually with the ordinary slip scraper, although in the construction of very large reservoirs wheeled scrapers are sometimes used.

In depositing the soil which is to constitute the embankment, it is

better to keep the parts which will become the faces higher than the center, thus leaving a channel all around through the whole of the embankment. At the close of each day's work care should be taken that this channel be continuous, and that the top of the embankment be about the same height all around, so that water may be pumped into the channel in the heart of the bank, thoroughly soaking it. In soils at all likely to seep it is very important that the precaution of soaking the bank daily as it is built be observed. If not made too soft in the evening, it will usually be in condition to tramp in the morning, and this should be done by driving repeatedly around on top of the embankment made. If each day's work is treated in this way, there will be little trouble from seepage through the bank of the completed reservoir.

The crumbling soils of Kansas will usually take about the correct form for a bank as deposited from the scraper and under the tramping here recommended. Some who prefer to have the banks steeper than they are usually left in this way trim them up with a shovel, afterwards sodding to prevent further crumbling. This answers very well for the outside of the dam, and sod used inside, as shown in fig. 1, is a protection against washing until the soil shall have become so thoroughly settled as to be less affected by the action of the waves. If the reservoir be small, it is sometimes inexpedient to take from the interior the entire amount of earth required for the embankment. Experience has shown that soil near the surface more readily becomes a water holder than does that from the substratum. In any case it is not safe to employ the gravelly subsoil which prevails almost everywhere in the larger valleys of western Kansas.

After the completion of the bank, the next work is to make the bottom of the reservoir water-tight. This is done by plowing the entire area to a depth of 3 or 4 inches, harrowing it fine, and then pumping in enough water to cover the entire bottom—if, indeed, it does not seep out too fast to admit of this. In any case, water should be pumped in until a considerable area is thoroughly soaked. As soon as this is settled sufficiently, so that heavy animals will not sink in more than 6 or 8 inches, horses or cattle are turned in and driven around over the water-soaked area until it becomes hard. Then more water is pumped in and a larger area soaked. It is usually found that after the first partial soaking and the subsequent tramping the entire area of the bottom may be covered with water. Enough water should be put in to thoroughly soak every foot of the area, so that it would be dangerous to immediately take large animals into it. After a few days, however, this will have settled so that animals may be safely driven over it, when it should be tramped continuously until it becomes so hard that the hoofs of the animals scarcely mark it. Such puddling rarely fails—even in very open soils and in those which seem to be nearly all sand—to make a reservoir so tight that the

SMALL RESERVOIR, SHOWING WINDMILL AND OUTLET, AT GARDEN, KANSAS.

seepage under 4 feet of water is insignificant. In rare cases it may be necessary to throw in manure, or at least straw or hay, and again soak and tramp, but generally there is enough organic matter in the surface soil to puddle sufficiently without the addition of any other material. Some preparations have been advertised as linings for reservoirs, but the cheapest and undoubtedly the best lining is as deep puddling as can be done with heavy animals.

Every reservoir must, of course, be provided with a suitable outlet for the water, and unless careful attention to the pumping can be relied upon there should be also an overflow or waste-way. The outlet flume should be provided when the reservoir is laid out and before the banks are completed. The bottom of the outlet should be placed as low as the bottom of the ditch outside, as shown in fig. 2, but is usually not so low as the bottom of the reservoir inside, so that the water is not all drawn from the reservoir. It is found that reservoirs retain their ability to resist seepage better if never entirely drained. This is especially true in the winter season, when, if allowed to freeze, the puddling of the bottom frequently becomes so deteriorated as to necessitate renewal. The flume should be long enough to reach entirely through the embankment. It is usually made of 2-inch planks, with a clear opening of 6 by 8 inches. Where large areas are to be irrigated, making rapidity of supply essential, the box should be made larger, and for field work an opening of 12 by 16 inches will be found ample. It is not always necessary to use the full size of the opening, but the flow is regulated by the extent to which the valve or gate is raised.

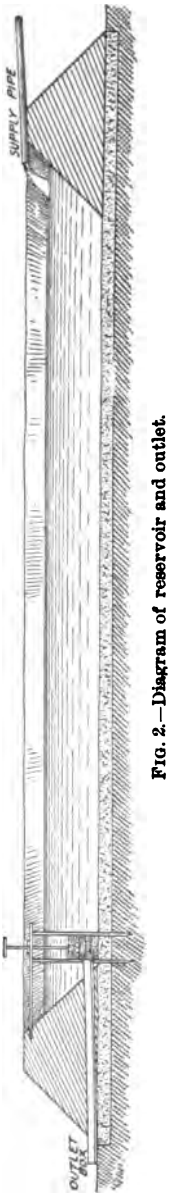


FIG. 2.—Diagram of reservoir and outlet.

Several forms of valve have been used. An excellent one is shown in the illustration, fig. 3, from a Kansas experiment station bulletin.[1] This gives a perspective view of the outlet box with guides attached for holding the valve or gate. This is faced with leather securely held by tacks. The gate is best operated by a carpenter's bench-screw attached to a suitable support and engaging a nut on the upright standard. An efficient gate is also shown in the illustration, Pl. IV, operated by a lever and rod extending through the outlet box. Whatever form of flume is used, it is better to have one or two bands of cleats around it, taking care that

[1]Small fruits by irrigation: Experiment station, Kansas Agricultural College, Bulletin No. 55, December, 1895, p. 134.

they fit water-tight to the planks. In placing the flume it should be very thoroughly embedded in the bank, care being taken to ram the earth firmly against the planks, especially on the under side, in order to prevent the water from creeping along between the planks and the earth. The extra work in properly bedding the flume is worth many times its cost in security against leaks.

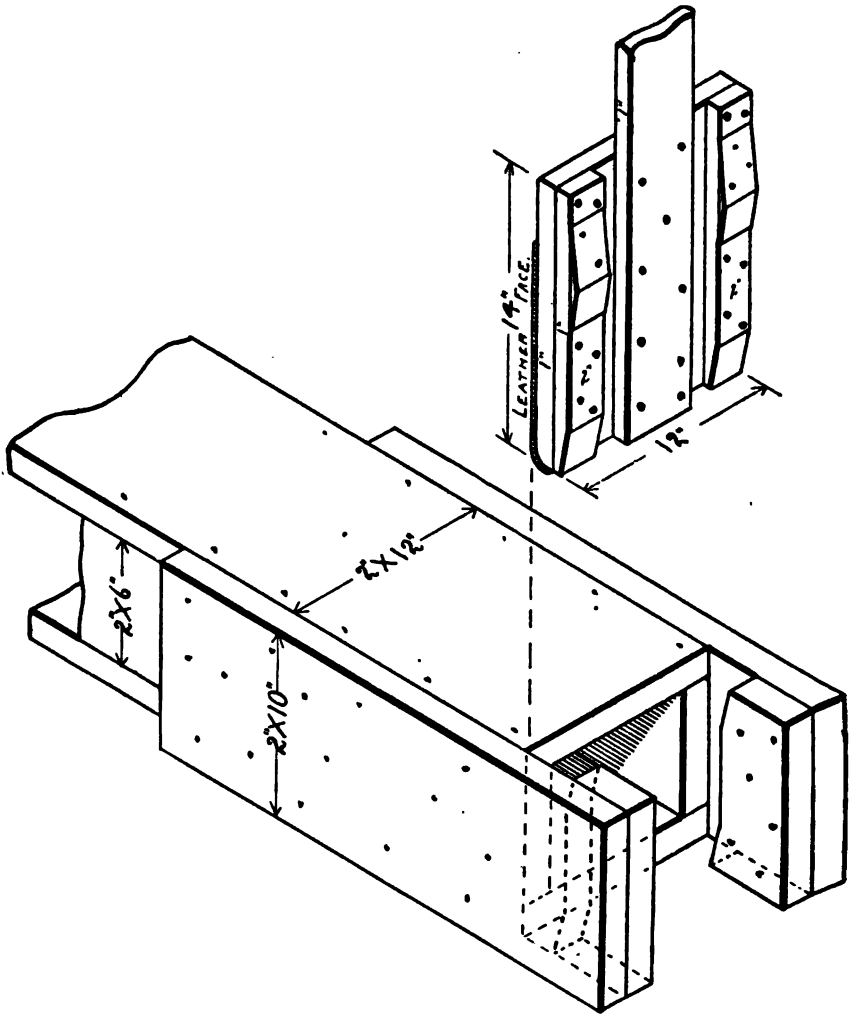


FIG. 3.—Reservoir flume and gate.

Little expense is needed to prepare an irrigation reservoir for the abode of edible fishes. It is requisite, however, to place wire screening in front of the gate, so that when water is to be drawn from the pond no fish can pass through the flume. A light framework is usually constructed, of such dimensions as to allow the gate to be opened without interfering with it, and this is covered with common wire netting, of the sort used for fly screens. This rusts out somewhat readily,

RESERVOIR AND IRRIGATED FIELD, AT GARDEN, KANSAS.

but is cheap and easily renewed. Screens of brass wire, while costing more at the outset, last much longer. The water as pumped from the wells into the reservoir is perfectly clear, and is usually at a temperature of about 58° F. This is not ideal water for the abode of carp; nevertheless, this variety has been more cultivated than any other, largely on account of its prolific increase. The growth of the carp is, however, somewhat disappointing, and this is probably due to the fact that, owing to the continual additions of the cold well water from the pump, the temperature of the water is below that at which the fish thrives best. Channel cat, crappie, and black bass have been found to do well. Some attempts have been made to grow trout in these ponds, but without success.

If irrigation reservoirs are not otherwise used in the winter, they form excellent ice ponds, and make available what would otherwise be an expensive luxury. But if water is continually pumped into the pond, especially in the more southern portions of the district, ice is but scantily formed. It is possible, however, for a farmer who has a reservoir to provide himself with a sufficient supply for the dairy and other purposes, even though he use his reservoir for irrigation during much of the winter.

DITCHES.

Not every tract of land has such conformation as renders irrigation practicable. Land the surface of which is formed into mounds of considerable magnitude may well be discarded, at least until that of more even contour shall have been brought under irrigation. Ridges and terraces are not especially objectionable features. It scarcely seems necessary to remark that irrigation is practicable only where water can be induced to flow over the land, and that water will not flow uphill, although the eye is often deceived and the novice at his first observation of the use of water through irrigation ditches receives the impression that in some parts of the work water is actually flowing up grade. And the most practiced are sometimes, indeed frequently, mistaken as to whether the surface of the land rises or falls in a given direction. It is therefore important, in the location of ditches, that a preliminary survey of the land be made; and it is a good plan to make a contour map of the land to be irrigated before locating the ditches. In irrigating from reservoirs it is essential, as before stated, that the reservoir be placed on the highest part of the land to be irrigated.

Ditches, as well as reservoirs, should be kept on land at least as high as, and generally a little higher than, that to which they are to supply the water. One of the largest and most successful irrigators of farm crops on the plains, C. D. Perry, of Englewood, Kansas, holds that in laying off the ditches it is necessary to forget all about directions of land lines and points of the compass, and be governed entirely by the contour of the surface to be irrigated (see Pl. VI).

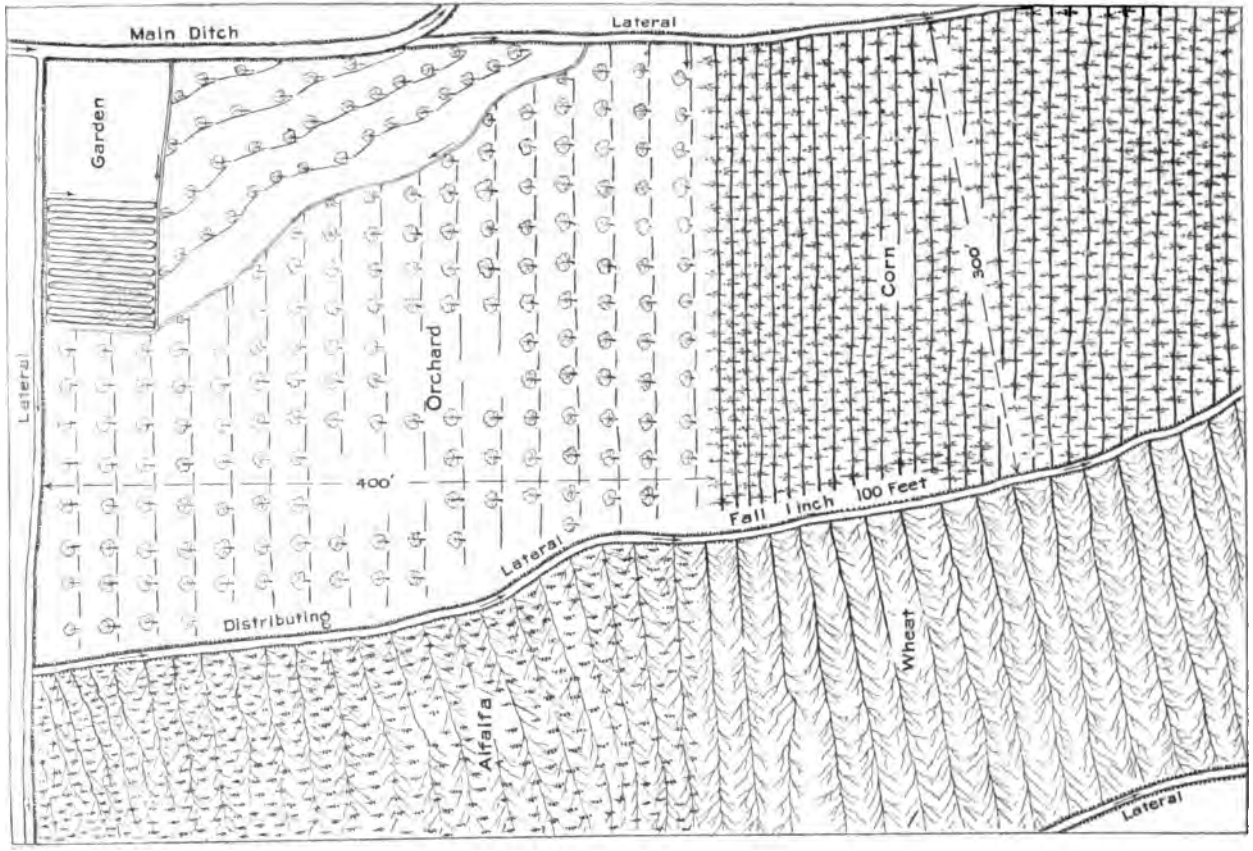
It is easily believed that the ditches must be carried along at a proper grade, and that the water can not be made to pass a hill by flowing up it, but only by following a course which gives a continuous though slight fall; but on the smooth surface of the plains, constituting not only the river bottoms but also the plateaus of the region, the unaided eye sees no reason why the water may not flow in one direction as well as another, or why it may not be made to follow the direction of the land lines without serious inconvenience. In some cases this can be done, but in others it is entirely impracticable.

These distributing ditches, or laterals, should be placed at such distances apart that the water may flow over the land from any ditch to the one next lower down the slope in so short a time that there will be no great difference between the amount of water taken up by the portions of the land on the different sides of the tract. This distance varies somewhat in different soils and on different slopes. Some have placed their ditches as far as 80 rods (1,320 feet) apart. Usually it will be found better to have the ditches not more than one-third this distance apart, and not infrequently it is better that the interval separating them be not more than 20 or even 16 rods.

Water flows when the fall is very slight. In large ditches, free from short bends, a fall of 12 inches per mile produces a good current, while in such ditches a fall of 30 inches per mile often produces such a current as to cut the banks. For small ditches, such as are used for distributing from pumped-water reservoirs, a considerably greater fall is admissible and even desirable, and for laterals from which the water is made to flow over the land a fall of 1 inch per 100 feet is the correct standard. Where it is possible, they should be laid with such courses as will give them this fall.

In size irrigating ditches vary greatly. In some cases the lister furrow, with the loose earth removed, is large enough, while for the conveyance of water for large areas canals several feet wide and carrying water 2 or 3 feet deep are sometimes used. When Mr. Perry was irrigating but 1,200 acres of land with water from the Cimarron River, his main ditch was 16 feet wide at the bottom and carried water about 2 feet deep, and its sides sloped about 2 to 1. As his irrigating operations were increased beyond this amount, he enlarged the ditch in order to have command of a larger supply. But irrigation from a pumped-water reservoir is usually confined to a single farm, varying from 1 to, say, 40 acres in extent. For the 40-acre farm a ditch as shown in Pl. VII, 5 feet wide at the bottom and carrying water 15 inches deep, with sides sloping 2 to 1, will probably be found as large as needed. The laterals leading from this main ditch over the land to be irrigated will generally be much smaller than this perhaps not more than half as large, or even less, according to the amount of land to be served from them.

In the construction of ditches the implements used are the plow



PLAN OF PERRY FARM, CLARK COUNTY, KANSAS.

DISTRIBUTING DITCH.

and some sort of appliance for removing the loose earth from the ditch. The line of the ditch having been determined, furrows are plowed, throwing the soil from the middle to either side, and the size of the ditch controls the distance between the furrows of the first round. Very many ditches are made by plowing this first round in such a way as to leave the width of one furrow of a 14-inch plow in the middle. This is then turned out toward one side, and another furrow is turned from the bottom of this last furrow toward the other side of the ditch. It now remains only to remove the loose earth from the bottom of the ditch to the top of the banks. This operation is most rapidly performed by an instrument called an "A," from its resemblance in shape to that letter. It is constructed of planks, usually shod with steel or iron along the lower edges. After being suitably weighted it is drawn by means of horses, apex first, through the ditch. By suitably placing the weight, one side of the A, usually designated the land side, is made to follow along near the middle of the bottom of the ditch, while the other side throws about half of the loose earth out upon one bank. The return trip throws the other half of the loose earth out on the other bank, and, with the exception of a little finishing with the shovel, completes the ditch.

Larger ditches require more furrows and further use of the A, but are constructed in essentially the same manner. So also, in a ditch which at any place is to be made deeper than the average, a little extra work is done with these implements in that particular part. It is important in the construction of ditches that the banks be made tolerably uniform in height, and be so constructed as to carry water somewhat above the ordinary level of the land. For the distributing laterals banks 6 inches above the general level of the land to be irrigated are about right; if they are made a little higher, so as to be 6 inches after settling, so much the better. For rapid irrigation the ditches should be at all times capable of holding water to at least 4 inches above the level of the field.

DISTRIBUTING WATER.

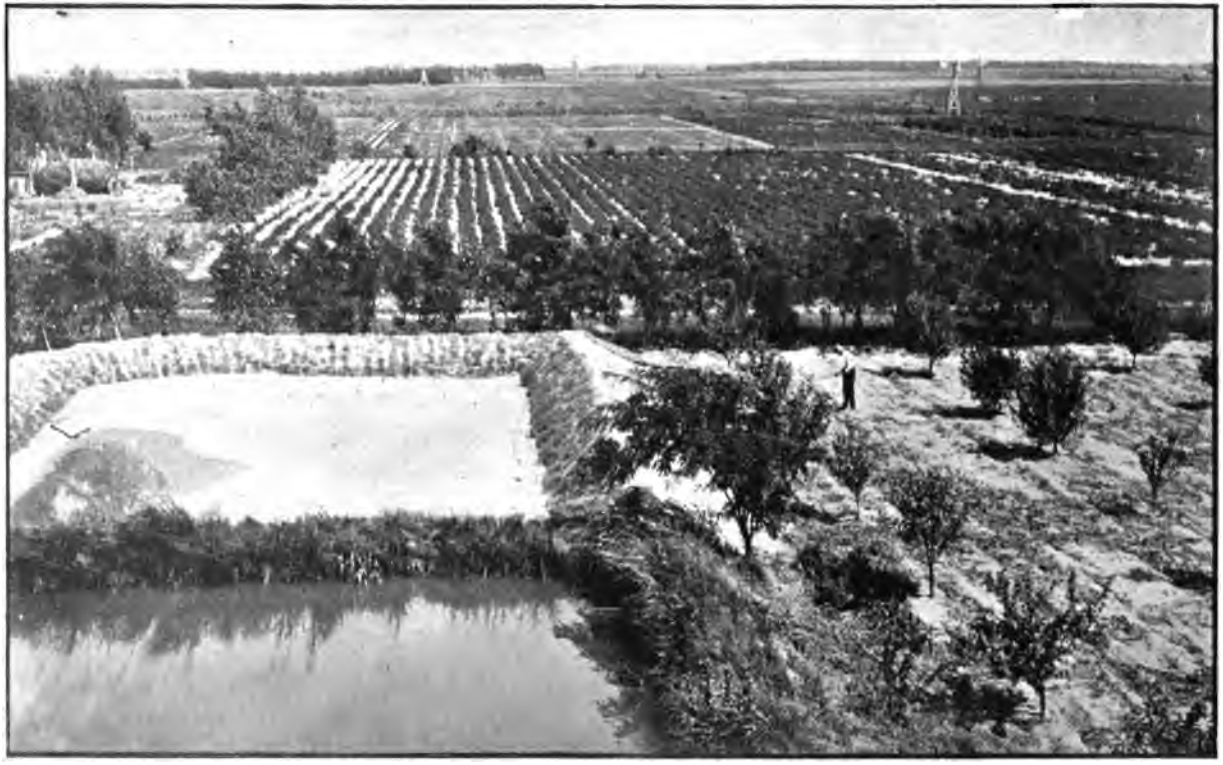
In irrigating it is necessary to have water spread with as much uniformity as possible to all parts of the land. Fields which appear to the casual observer to be entirely without features of undulation are often found, when inspected with a view to irrigation, to possess elevations and depressions not suspected before. The practical irrigator finds that an elevation no greater than the thickness of a man's hand may turn the water entirely around a portion of his ground. So, also, a very slight depression is always found by the water, and is liable to be overirrigated, water-logged, and thereby caused to settle, increasing the disparity of the surface. It is therefore necessary that almost every piece of ground which is to be irrigated should be graded.

Grading may be done either before or after the construction of the

ditches. It will usually be found that if the ditches are made first, or at least located, less grading will be required than would be considered necessary before the location of the ditches. There are various grading machines, all of which are operated by horsepower, and some of which are very simple. Some excellent graders are on the market at reasonable prices, but many farmers construct their own of planks, and with them do quite as good work as could be done with any machine built. Usually a few turns with the grader suffice to fill up a low place, and often at the same time to remove an elevation. It should be remembered that grading is of the nature of a permanent improvement. Once thoroughly done, it has never to be done again.

Water is thrown out of the ditches by means of dams, the use of which will be described presently. The most convenient form is the canvas dam. The materials used in the construction of a canvas dam are a piece of timber, usually a 2-by-4 scantling, long enough to reach across the top of the ditch from bank to bank; a small stick varying in length according to the width of the ditch to be dammed, but no longer than will lie across the bottom of the ditch without leaving any considerable space between the stick and the bottom; a brace or stick about one-third longer than the depth of the ditch, and a piece of canvas about one-third wider than the depth of the ditch and as long as the width of the ditch at the upper edge. The canvas is cut into a trapezoidal shape, somewhat resembling but larger than a section of the ditch. The long edge of the canvas is fastened to the scantling first described and the short edge to the small stick. It is well to have a little margin of the canvas below this short stick. The dam is placed by throwing the scantling across the ditch just below the point at which it is desired to divert the water, as shown in the illustration, Pl. IX. The canvas rests in the ditch, with the short stick lying across the bottom, far enough upstream from the location of the scantling to make the canvas nearly tight. The brace is placed with one end against the scantling and the other against the short stick, thus preventing the canvas from being washed back under the scantling. A little earth is thrown upon the loose edges of the canvas where it rests against the banks and against the bottom of the ditch, and the water is turned in. The weight of the water presses the canvas closely against the banks, so that there is scarcely any leakage. In some cases permanent dams with head gates are placed in the ditches, and this is more often done where ditches branch and it is desirable to divert the water to the one or the other branch.

FIG. 4.—Land grader.



RESERVOIR AND GARDEN, AT GARDEN, KANSAS.

CANVAS DAM IN DISTRIBUTING DITCH.

A more primitive dam is sometimes made of earth, and such a dam is quite effectual and easily made in very small ditches. Sometimes a board is cut into the banks, and earth thrown in above it, making an effectual dam for ditches of considerable size; but for general purposes, where it is not worth while to put in permanent dams with flumes, canvas dams are most effective, and are placed and removed with less labor than any other. It is well that the irrigator be provided with at least two canvas dams suitable for each size of ditch from which he wishes to divert water.

METHODS OF WATERING.

That which has gone before is preliminary to the final object of applying water to the land at such times as the interest of the farmer or gardener suggests. There are two principal methods of watering, and a third is especially attractive to the novice and the amateur, and is not without its uses in some cases. For sowed grains, meadows, and pastures water is supplied to the land by flooding; that is, by allowing it to flow as completely as possible over the entire surface, but only in such volume as will not cause washing. For crops planted in rows and for orchards irrigation by furrows is generally preferred. The third method is by underground pipes, into which the water is passed, to be distributed through the soil by capillary attraction or surface tension, rising from below to near the surface, rather than passing from the surface downward, as in the other two methods.

Irrigation by flooding presupposes that the work of grading has been thoroughly done and that the ditches have been laid out and constructed with care. Take, for example, a meadow which has been thus prepared. The irrigator proceeds to a point in one of the laterals leading through this meadow 400 feet down the lateral from the point at which it enters the meadow. Here he places his canvas dam in the lateral, then admits the water. It will be remembered that the banks of these laterals are constructed so as to be 6 inches higher than the surface of the adjacent field. As soon as the water has risen 4 inches above the level of the field at the dam, or within 2 inches of the top of the bank, the irrigator makes a small opening in the bank just above the dam to the level of the water. At a distance of a rod or so farther upstream he makes another small opening, and so on throughout the 400 feet to the edge of the meadow. By this time the water is pouring out through all of these openings, giving a small stream at each. These streams spread over the ground and very soon widen into a broad sheet, which, with much irregularity of front, spreads downward toward the next lateral. If the grading has been well done, so as to give a uniform surface to the meadow, there should be no dry spots left after such an irrigation. If the grading has not been perfectly done and the water has inclined to flow around certains areas,

it is necessary for the irrigator to take his shovel and, beginning at the point where the water begins to flow around, open a shallow channel through the highest part of the dry area, thus leading the water from the upper side and securing practically uniform irrigation. The water is allowed to continue running until this section of the meadow has been thoroughly moistened to such depth as the irrigator desires. With fresh ditches it is necessary to watch carefully that none of the openings in the bank becomes seriously washed and gets too large. When such trouble begins it is quite easily remedied by throwing in a shovelful or two of soil. When the ditches have become well settled, little trouble in this respect is experienced.

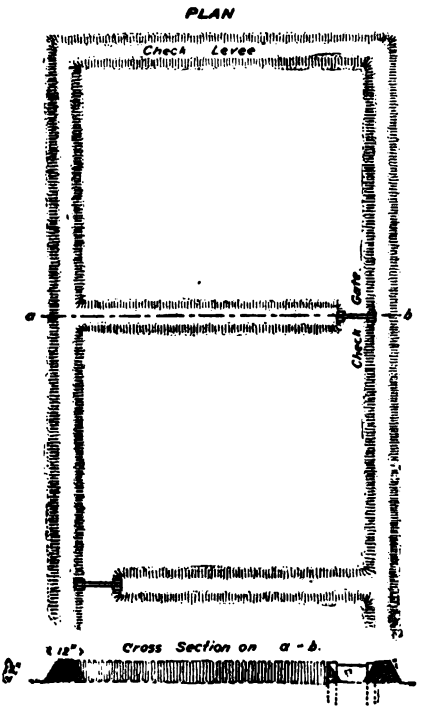
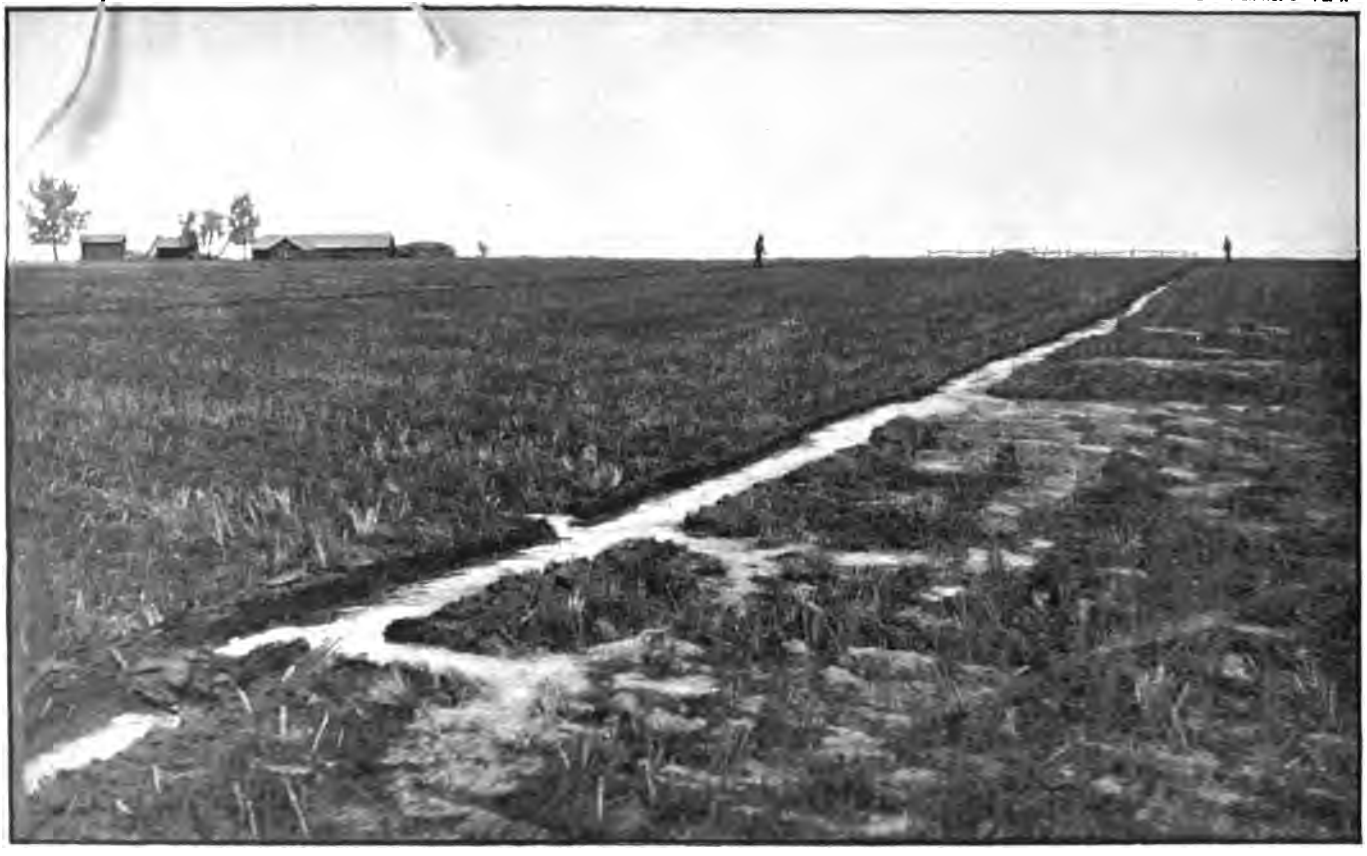


FIG. 5.—Diagram illustrating flooding in rectangular block.

While the water is flowing over this first section of the meadow the irrigator places a second canvas dam at a point about 400 feet farther down the lateral than that at which the first was placed. When the irrigation of the first section is completed, the dam first placed is removed and the water is allowed to flow down the lateral to the second dam. Openings are made in the ditch as before and the second section is irrigated in manner precisely like the first. The dams are thus removed to positions successively 400 feet farther downstream, and sections of this length are thus irrigated. The same course is pursued with each of the other laterals until the entire meadow is gone over.

It will be remembered that in speaking of ditches the proper fall was stated to be 1 inch to 100 feet. By making the opening nearest the dam so that its bottom is 4 inches above the level of the field, the water will rise to that height, and the bottom of the last opening, 400 feet farther up, will be just at the field level. If for any reason it has been necessary to give the ditch a greater fall than 1 inch to 100 feet, the dam is placed at correspondingly shorter intervals, unless the banks of the lateral have been made so high as to carry water more than 4 inches above the level of the field. For subsequent irrigations, if the ditches have not been disturbed, the dams may be placed in the same positions as at the first irrigation, and no new openings in the bank will be necessary,



EARTH DAM IN DISTRIBUTING DITCH.

the old openings being as available as at first, for on the removal of any dam the water immediately falls, so as to cease flowing through the openings above, the entire fall being 4 inches to the level of the openings of the next lower section. It is never necessary to close the openings when once properly made, and the only attention needed is to prevent or repair washes and to maintain all parts of the bank at sufficient height to prevent overflows other than at the points desired. Where an abundant head of water is available and old and well-settled ditches are used, it is often possible for the irrigator to attend to the dams and openings in more than one lateral, thus increasing the rapidity of the work. This method is applicable not only to meadows and such sowed crops as wheat, oats, rye, barley, etc., but it is sometimes used for corn or orchards, and indeed for almost everything except potatoes.

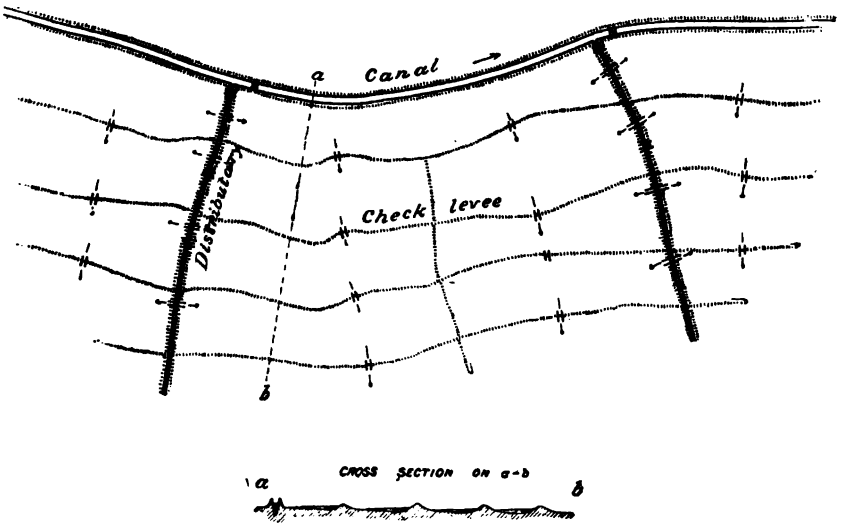


FIG. 6.—Diagram illustrating flooding within levees on irregular ground.

A modification of this system is used for some garden crops. Thus celery requires frequent and copious irrigation. The ground on which it is planted may be made into perfectly level beds, each having a border a few inches high completely inclosing it. The celery is irrigated by allowing sufficient water to run into this inclosure to cover the ground and settle into it until it is sufficiently moistened. Some celery growers irrigate in this way every two or three days from the time of planting until just before the celery is gathered.

This bed system is sometimes applied to field work. The borders are made somewhat higher, and the beds are made to contain in some cases several acres each, according to the head of water available and the configuration of the surface. In field work the borders are made on contour lines, and are thrown up with the plow, and so rounded

over the surface as to admit of mowing or cultivating over these elevations, so that the area of the embankments is neither wasted nor left to grow up in weeds.

This bed system, while at one time received with much favor for field work, is gradually giving way to the flooding system, as previously described, and to the furrow system, to follow.

In preparing for irrigation by the furrow system, the distributing laterals are made in all respects as described for the flooding system, except that it is practicable to have them somewhat farther apart. The rows of crops, as corn or potatoes, are made to terminate at the laterals from which they are to be irrigated, but it is not essential that they meet these laterals at right angles. When the water is to be applied, small furrows are made down the rows, care being taken that the loose earth does not roll back into the furrows so much as to obstruct them at any point. These furrows extend from one distributing lateral to the next. Canvas dams are used as in flooding. The openings in the laterals are made at suitable intervals, and the water from each of these openings is turned into four or five furrows and allowed to trickle slowly down the furrows to the next lateral, and to continue flowing until the entire section is thoroughly irrigated.

The size of the streams needs careful and intelligent attention. If the water be allowed to rush down the furrows so rapidly as to become turbid by picking up the finer particles of soil, these particles will be deposited farther down the furrows as the volume of the stream becomes smaller and the current becomes less on account of the absorption of a part of the water in the soil traversed. This deposit of fine particles is apt to act as a cement to the furrows and prevent proper absorption of the water. It is possible by the very rapid use of water to cause it to flow through the entire length of the furrows without effectually irrigating the soil. The novice at irrigation is almost sure to be surprised at the action of an irrigating stream in the furrows in a soft, plowed field. If the stream is very small, it may entirely disappear in the first rod or two of the furrow. If the stream is very large, it may carry away a considerable part of the soil from the first few feet or few rods of the furrow, and, as already stated, flow through without accomplishing the purpose of effectually moistening the land.

A properly regulated stream should flow through a furrow without becoming very turbid at any point, and should progress continuously, though slowly, throughout the length of the furrow. After it has flowed for a time, varying with the nature of the soil from a few to many hours, the land should be so thoroughly irrigated as to make it, especially if newly plowed, too soft to walk over without miring. Where the soil is of a flocculent structure and contains considerable vegetable material, this thorough irrigation may take place by the

FURROW IRRIGATION.

furrow system without greatly changing the loose and flocculent structure so desirable for rapid growth of vegetation. This is the acme of irrigation. Not every soil will retain this open structure, even under the most skillful handling of water. With many soils it is found that the effect of the artificial application of water is much like that of an exceedingly heavy and dashing rain, solidifying the soil by breaking down the open structure. It may be said that, as generally applied, irrigation leaves the soil compact and in condition to become very hard as it dries.

CULTIVATION.

The compacting of the soil after irrigation is remedied by cultivation of the surface as soon as the soil reaches a condition to be worked. This cultivation after irrigation serves the double purpose of checking the growth of weeds, which is sure to be copious, and of leaving a soil mulch of loose earth over the surface, which prevents the rapid evaporation of the moisture stored in the subsoil. The importance of cultivation after each irrigation can not be overestimated. In general the application of water without the subsequent cultivation is of little value, and, indeed, in many cases it is absolutely detrimental. The general experience is that, with the average soil, after the application of water the ground soon becomes very dry and very hard, and evaporation proceeds to rob both the soil and the subsoil of moisture with surprising rapidity. If the irrigator thinks to remedy the case by another irrigation, he usually only makes the matter worse, for the soil by this time, especially that along the borders of the furrows, has become quite thoroughly puddled, so that the second application of water with no intervening cultivation amounts to little more than flooding over the surface, with but slight moistening of the undersoil.

It may be stated in general that the irrigator who fails to cultivate soon after each irrigation will make a failure of irrigation. Indeed, in almost any part of the Great Plains, if either irrigation or cultivation must be omitted, it will be better to omit the irrigation than the cultivation for all such crops as admit of cultivation. The case with meadows and with sowed crops in general is somewhat different, the soil being to some extent protected and supported against excessive settling by the general distribution of the plants and roots. It is not improbable, however, that in the case of annuals, as wheat, rye, barley, and oats, it will be found profitable to make the drill rows far enough apart to admit of cultivation while the plants are small. In the case of meadows, especially with alfalfa, the influence of the extensive root growth is such as to keep the soil in condition favorable to rapid growth without cultivation. It is noticeable, however, that even alfalfa shows the marked influence of cultivation where a meadow of this legume joins a cultivated field.

SUBIRRIGATION.

The application of water by means of furrows placed at a considerable distance from the plants to be watered can be beneficial only in soils allowing a considerable lateral movement of the water. This percolation may take place in certain soils through a space of several feet or rods, while in others the influence of the water apparently is not felt for more than a few inches. In cases where the soil and subsoil have a structure such that water moves laterally through them with considerable ease, the theoretically perfect method of applying it is through pipes laid underground below the reach of the plow and perforated, so that when filled the moisture will be uniformly distributed near the roots of the plants. This does away with all losses from evaporation and from saturating the sides and bottom of the open ditches. Unfortunately, however, this method has been found practicable only to a limited extent. Many soils do not transmit the water freely, while others are underlain by a gravelly or open subsoil through which the water escapes downward with far greater rapidity than it can move sideways. Another serious obstacle to the success of this form of irrigation lies in the fact that the little roots of the trees and plants are induced by the moisture to reach out toward the pipes, seeking every crevice or perforation, and soon stopping these up with interlacing rootlets. In California many instances are given where great expense was incurred in laying out an elaborate system of perforated or porous pipes. Irrigation through these was highly successful for one or two years, and then became less so, until the method was abandoned and the pipes taken up or else openings made to the surface, so that the water could come up and spread as from a hydrant over the plat to be wet.

The term "subirrigation" is often applied to the conditions where the subsoil is saturated either artificially or even naturally. For example, many lowlands along streams are commonly said to be subirrigated from the fact that the underlying gravels are filled with ground water which extends up high enough to be available for the use of deep-rooted plants. The word is also applied to similar cases where, by excessive use of water on lands higher up, the low grounds have been so completely filled by seepage that it is no longer necessary to flow water over the surface. This is, however, hardly a proper use of the term, as it can better be confined to the intentional application of water beneath the surface by pipes or similar devices.

The method of irrigating by underground pipes is one that appeals very strongly to the fancy of the novice. It has been repeatedly tried, and in most cases has been abandoned. This does not necessarily prove that the plan is useless or impracticable, and the fact that some have continued its use makes it worth while to describe it and to examine somewhat the conditions of its trials and the probability

SATURATING GROUND.

of its usefulness. The plan is, in general, to place porous drain tiles far enough beneath the surface of the cultivated land to be out of the way of the plow and other implements of cultivation, and to have the lines of this tile so connected with the source of water supply that they may be filled at will. Reports of the use of this method in California state, as noted above, that the roots of the trees and plants penetrated the tile at the joints, or at any opening where the water could get out, and formed mats of small rootlets within the pipe, so as to effectually obstruct the flow of water. In the gravelly and open soils of Utah it was found that on emerging from the pipe lines the water was very little inclined to distribute itself laterally, but yielded to gravity and went down, so that only narrow strips were well irrigated, and these at considerable depth below the surface, the water having little inclination to rise above the pipe lines. At the Wisconsin experiment station the water came to the surface above the pipe lines, but the spaces between were not well irrigated. A photograph of a tile-irrigated field or plat showed by dark lines the location of the pipes, while the intervening surfaces were entirely dry.

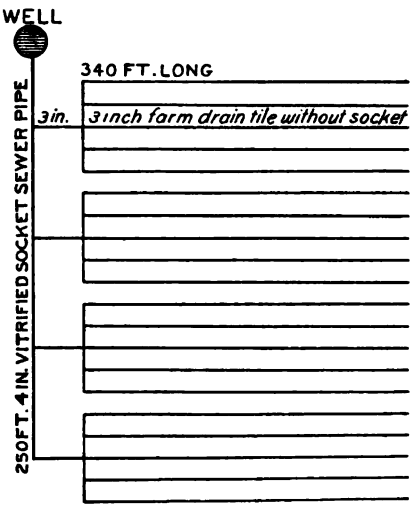


FIG. 7.—Plan of subirrigating system.

In Osborne County, Kansas, very satisfactory results have been reported from pipe irrigation, the water having been distributed laterally, so that almost ideal irrigation was obtained. The objection noted in California is one for which it is difficult to conceive an effectual remedy. It is undoubtedly true, however, that a stoppage in a pipe may be easily located, and since the pipes are placed at no great depth below the surface, it should not be a serious task to remove a single obstruction. But if the stoppages should be very numerous, the expense of keeping the lines open might exceed the advantages claimed for the system. In Utah the tendency of the water to go immediately downward instead of laterally was due to the open, gravelly subsoil. A consideration of the description of other experiments suggests that the difficulty encountered—that of the water coming to the surface immediately over the pipe lines, but not distributing well laterally—may be overcome by a modification of the work. It appears that in these experiments the pipes were put in trenches in the subsoil and the surface cultivation was conducted in the usual way. The water had little opportunity to circulate laterally until it had risen to

the bottom of the cultivated stratum. In the experiments in Osborne County, Kansas, the entire subsoil was broken to the depth at which the pipes were laid. The water moved laterally over the compact, undisturbed lower subsoil and rose to the surface quite uniformly over the entire tract. Possibly if the subsoil in the Wisconsin experiments had been treated in the same way, the results might have been modified and made favorable rather than unfavorable.

The plant of one of the successful tile irrigators of Osborne County, Kansas, Mr. Andrew Linn, is described as follows: The ground was plowed 6 inches deep and subsoiled about 8 inches, altogether stirring the soil to the depth of about 14 inches. The ground was plowed north and south, the tiling laid east and west. The land slopes slightly to the east and south. An arrangement is made to use the plant as a drainage system when there is too much rain. Three-inch tiles are laid 15 inches below the surface and 10 feet apart. Unglazed drain tiles are used, but they are so hard that practically no water passes through the pores, the outlets being at the joints. These joints are closed with cement, with the exception of about an inch on the underside of the tiles. If no part of the joint is cemented, the water flows out too rapidly and is not evenly distributed. Mr. Linn laid and cemented his tiling on 2½ acres in ten days. The ditches for the tiling were made with a lister plow and spade. The pump to supply water to the tiling has a capacity of about 20 gallons per minute.

The diagram, fig. 7, shows the plan of the system. The water is carried from the pump in a wooden conductor and flows into a barrel sunk into the ground about 10 feet away. A 4-inch sewer pipe from this barrel is laid in four sections extending southward across the west end of the plat to be irrigated. At the end of each section the pipe discharges its water into a barrel (not shown in the diagram), also sunk into the ground. From this barrel a 3-inch pipe, 8 feet in length, is laid eastward, where it communicates with a 3-inch pipe laid north and south about 40 feet. To this pipe are connected five 3-inch drain tiles extending eastward entirely across the plat and 10 feet apart. The lot is thus divided into sections, each independent of the others, and facilitating the irrigation of any section at will.

Mr. Linn is satisfied with the results of irrigation with this plant, but as yet no comparison has been made with those obtained by surface irrigation under otherwise similar conditions. The cost of such an arrangement is certainly against it, and will probably, for a long time at least, preclude its use except for gardens or for farming on a very small scale. But the experiments of Mr. Linn and some of his neighbors have shown that with such soil and subsoil as they possess it is perfectly practicable to get a good distribution of water by means of underground pipes. Their plan has been to pump the soil and subsoil full of water during the fall and winter, saturating it to a depth of 6 or 8 feet.

After this it was necessary only to supply the water transpired by vegetation and lost by evaporation, the loss being very small on account of the fact that no crust was formed on the surface, and the flocculent, open structure of the soil was little interfered with by this method of applying water. It remains to be seen whether the plan of cementing the joints of the hard-burned tile, except an inch on the under side, will prevent the entrance of roots to the extent of stopping the circulation of water through the pipes. This method has been used also by Dr. Hudson, of Osborne, who has expressed satisfaction with the results. Other than tile pipes have been used for this purpose. Small pipes made of galvanized iron and perforated with very small holes, or preferably with an open seam, have been used and satisfactory results reported. The following description has been condensed from a statement given by Mr. Alex. Richter, of Hollyrood, Kansas, who has used the open-seam pipes.

The first precaution is to ascertain whether the structure of the soil and subsoil is such that subirrigation is practicable, as it is a useless expenditure of money to lay pipes where the conditions are such that the water will not spread laterally to the plants. In some localities the subsoil is so porous that the water applied beneath the surface sinks immediately and can not be had by the roots of any of the plants except those in the immediate vicinity of the source of supply. This is especially the case on the bottom lands along streams where the surface soil rests upon gravel or beds of sand. Where, on the contrary, the subsoil is comparatively impervious, and above this the structure is such that the water is transmitted horizontally, systems of subirrigation can be introduced to great advantage. For example, the following experiment was tried: During a dry season a pipe 10 feet long was laid 10 inches deep in the middle of four rows of string beans, these being about 5 feet apart. Into the pipe 12 quarts of water were poured, and the same amount was sprinkled on four other rows of string beans in all respects similar to the first. In the case of the rows watered by the pipe the beans did well, while in the other rows they died. The same amount of water was given to each.

In 1895 many experiments were made by different farmers, some putting pipes in rows 5 feet apart, others 8 or 16 feet, and in one case 27 feet. Different depths also were tried, some being 14 inches, others 18, and still others 2 feet. During the first five months nearly all of these were satisfactory, but after that period difficulty was found by the persons who had laid the pipes from 18 to 24 inches beneath the surface. By digging down it was found that the deeper pipes had been placed so low as to be embedded in the clay subsoil, and that this did not allow the water to spread freely. By raising the pipes about 6 inches, well above the top of the clay, the water percolated freely. For vegetables it was found that pipes give the best success when laid from 8 to 10 feet apart, while for orchards a single row of

pipes was sufficient between alternate rows of trees, these pipes being placed from 10 to 12 inches in depth. It was also found that the moisture was rendered more efficient by using fertilizers.

One of the most common mistakes at first made has been in giving too great a slope or inclination to the pipes. If laid on ground which has a decided fall the water runs to the lower end before it can escape in considerable part through the opening along the side. For this reason the pipes should be laid very nearly level, but if a considerable slope can not be avoided it has been found best to have cut-offs in the pipe every 10 or 20 feet to check the flow. Another way is to run the main pipe on the down grade and connect this with irrigating pipes branching from it with suitable valves or cut-offs, so that the water can be turned into the branches. The preferred length of irrigating pipe is about 200 feet. Sometimes this can be connected at both ends with the main supply pipes to advantage. The main supply pipe is proportioned according to the amount of water to be carried. In general for gardens and orchards it is 1¼ inches in diameter. The sheet-iron irrigating pipe leading from this has an open seam along its length and is usually seven-eighths of an inch in diameter, although smaller sizes can be used for flower beds. The cost varies according to the amount used, but in one case where 3 acres were provided, 2 of these being orchard and the remaining acre devoted to potatoes, watermelons, and other vegetables, the entire cost was $63. In this case the watermelons alone paid the cost of the pipe. One man can lay nearly 3,000 feet in a day, covering it up by means of a plow.

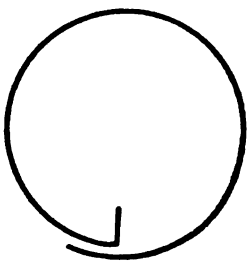


FIG. 8.—Section of open-seam pipe.

There is a notable difference in the distribution of moisture when the subirrigating pipes are laid above the surface of the clay and when they are put down in it. In the first case, when the pipe is buried in the pervious soil slightly above the impervious clayey subsoil, the water spreads laterally upon the surface of the latter, moistening the ground upward while spreading out beneath the surface. In the second case, when the pipe is within the clay, the water can not spread laterally, but rises slowly and moistens only a narrow belt immediately above the pipe, not finding its way as rapidly as in the other case along the surface of the clay.

This difference in behavior is illustrated by an experiment in which two pipes were laid above the subsoil and five pipes below the clay. The two pipes were able to deliver far more water than the five more deeply buried. An examination by a test pit showed that although the surface was dry above the five pipes, there was standing water in the clay. This fairly uniform distribution of water from the pipes when laid above the subsoil is said to obviate the difficulty found with the roots of trees. The great objection to this form of subirriga-

tion has been that after one or two years the fine roots of plants seeking out the water inclose the conducting pipe and penetrate every opening or crack, finally completely obstructing the flow of water. Where, however, the moisture is distributed uniformly through the soil, the roots are not impelled directly toward the pipe. Cases have been reported where pipe has been used for three years successfully at a distance of only about a yard from a row of trees.

AMOUNT OF WATER REQUIRED.

There are two ways in which quantities of water used in irrigation are expressed. One is in terms of the rate of flow, as, for example, that of a river; the other is in quantities of water, such as would be held by a reservoir. In the first case we speak of a stream as averaging through the month of August 10 second-feet or 500 miner's inches. In the second case we speak of a reservoir as holding, in round numbers, 6.46 million gallons, or 862,000 cubic feet, or 19.8 acre-feet. Each of these can be converted into the other by simple computations. Where water is spoken of according to the rate of flow, the total volume can be obtained only by assuming a certain length of time during which the flow continues. On the other hand, the volume of water, as, for example, that stored in a reservoir, can be converted into rate of flow by figures based upon the number of days or seconds during which the quantity is to be discharged.

In discussing rates of flow of a natural stream, the cubic foot per second or second-foot has been generally adopted as the standard, and is rapidly displacing the older, indefinite term—miner's inch.

The cubic foot per second, or second-foot, is the rate of delivery of a stream 1 foot wide and 1 foot deep, flowing at the average rate of 1 foot per second. The quantity is, of course, independent of the shape or velocity of the water; a second-foot will be delivered by a pipe 6 inches in diameter in which the average flow is a trifle over 5 feet per second, or by a ditch having a cross section of 4 square feet and a sluggish current of only 3 inches per second.

The miner's inch is a unit adopted for convenience by the hydraulic miners of the West, and, being easily arrived at through rough devices, has been largely employed throughout the arid region in estimating the quantities of flowing water. The chief objection to it is its indefinite character. One miner's inch may be 20 or 25 per cent larger than another, although both are measured according to established rule or customs. In early days, when water was abundant and it had little value, there was no especial demand for accuracy in its measurement, and the crude devices sufficed for all practical purposes; but when the streams came to be used for agriculture and it was appreciated that values resided in the flowing water rather than in the land, it made considerable difference to a farmer whether his miner's inch of water was large or small. To avoid confusion and litigation, the term "miner's inch" has therefore been largely done away with

and quantities are given in fractions of a second-foot. In California the miner's inch is now given as one-fiftieth of a second-foot, while in Colorado and many other of the Rocky Mountain States it is nearer the fortieth part of a second-foot. In other words, the Colorado miner's inch is considerably the larger.

The second method of stating the quantity of water—that by actual volumes rather than by rate of flow—is in all respects the more accurate and desirable, and is the only practicable means in localities such as those on the Great Plains, where water must be pumped or stored and is not running continuously to waste when not used, as is the case along the larger streams of the arid region. The units employed may be the gallon, the cubic foot, or the acre-foot. The United States gallon, as defined by statute, contains 231 inches; 7.48 gallons make a cubic foot, or 1 gallon is 0.13368 of a cubic foot. The chief disadvantage of the gallon as a unit is that it is too small and requires large figures to express the amount needed for irrigation. It has also the additional disadvantage that there are other gallons of other sizes in use, so that confusion occasionally arises.

The cubic foot is a definite quantity and is very convenient for use in computations of the amount of water required. By its use the capacity of reservoirs can be readily computed, since their dimensions are usually expressed in feet. It is, however, like the gallon, too small for convenience in many estimates, and in practice it has been largely replaced by the acre-foot. This latter term implies a quantity equivalent to the amount of water covering 1 acre to the depth of 1 foot. In other words, 1 acre-foot equals 43,560 cubic feet. This quantity—an acre-foot—does not imply that the water must be spread out 1 foot in depth, for the 43,560 cubic feet can be placed in a reservoir of any shape and still be an acre-foot. It may be held, for example, in a pond 100 feet square and to a depth of a little over 4.3 feet, or it may be in a tank 20 by 50 feet and 43.56 feet deep. There is a convenient relation between the acre-foot and the cubic foot per second, or second-foot. The latter flowing for one day (twenty-four hours) very nearly equals 2 acre-feet; that is to say, a stream 1 foot wide and 1 foot deep, flowing at an average velocity of 1 foot per second, will in one day, or 86,400 seconds, cover a surface of 1 acre to a depth of very nearly 2 feet.

The term "duty of water" has been employed to express the relation which exists between the quantity of water used and the area of land irrigated. For example, if a stream of water equivalent to 1 cubic foot per second irrigates 100 acres, the water duty at that place is stated as being 100 acres to the second-foot. This water duty may be arrived at from two opposite directions. First, as given above, by taking actual instances of the measured amount of water applied; and second, by starting at the other end and estimating the theoretical amount which the plants require and the quantity which must be wasted in wetting the ground before the water can be available for the

need of the plants. Neither of these is wholly satisfactory, and there has not as yet been obtained a sufficiently large body of facts to enable conclusions of general applicability to be drawn. Taking any one crop through successive years, the amount of water actually used varies so widely that it is doubtful whether any figures yet published can be implicitly relied upon.

A large number of experiments have been carried on, not only in Europe but in this country, to show the amount of water exhaled by plants. The results of these, as above stated, are discordant, but as a rough statement it may be said that the plants have transpired during their growth a weight of water from 300 to 500 times that of the weight of dry matter. In this country various agricultural stations have obtained and still are obtaining data bearing upon this point. Among the best of the published results are the series of experiments conducted by Prof. F. H. King at the Wisconsin agricultural station. These are of particular value in this connection as showing the amount of water required by plants even in a humid climate. The results of the observations for 1892 show the following amounts of water consumed per pound of dry material produced:

Crop.	Water consumed.
	Pounds.
Barley	375
Oats	526
Corn	317
Clover	564
Pease	477

The data given above have been combined with those obtained for 1891 and computed in other units, giving the corresponding depth of water used in the production of the plants. These results are shown in simplest form in the following table:

Crop.	Year.	Water consumed.
		Inches.
Barley	1891	13.2
Do	1892	23.5
Oats	1891	19.7
Do	1892	19.0
Corn	1891	26.4
Do	1892	25.1
Clover	1892	29.7
Pease	1892	16.9

From the above table it is to be observed that the least amount of water used was by the barley in 1891, and it should be noted that the product for this year was only about half that for 1892, while nearly double the amount of water was used. It is probable, therefore, that if the barley had received or used as much water as the same crop in 1892, the production of dry matter would have been greatly increased.

It has been found that there is a great range in the amount of water employed by various plants in the process of building their tissues, and that not only do the different species stand widely apart in this respect, but even individuals of any one species at the successive stages of life or with alternations of climatic conditions transpire water more or less freely. As previously noted, the experiments, when reduced to a common basis, show a wide range in results, depending largely not only upon the conditions under which the tests were carried on but also upon the assumptions necessarily made in reduction to the same form of statement. Thus the water used by a crop of wheat is from 9.3 to 29.8 inches in depth, averaging 17.9 inches; by barley, from 4 to 30 inches; the same experiments in successive years obtaining 13 and 23.5 inches, the difference, however, being in part accounted for by the increase in yield.

In actual crop production, however, it is necessary not only to satisfy the thirst of the plant but also to fill certain demands of the soil necessitated by its composition, structure, and exposure to the air. A certain amount of water must be given to the soil before the plant can obtain any for itself, and, according to the skill of cultivation, more or less of this water will be taken up directly by the air or by weeds. The process of getting the water to the crop, usually in open-earth channels, is also more or less wasteful, so that beyond the plant's needs there is always to be added a variable percentage to cover these various losses. Many of these losses may be reduced or prevented by more perfect systems of irrigation and cultivation, but there is always a limit to expenditures in this direction set by the market value of the product. In other words, it will not pay to push water economy in this direction beyond moderate efforts.

To obtain valid conclusions as to the total amount of water required by the plant, together with that portion lost in transit in the irrigating channels and in the soil while waiting for the demands of vegetation, it is necessary to resort to the results of field tests made in various localities under local conditions of soil and climate. There are, unfortunately, comparatively few data as yet sufficiently complete for generalization, and these, as might be expected from an analysis of the matter relating to plant transpiration, offer wide discrepancies.

Experimental data are still lacking as to the exact amount of water required for the proper moistening of plains soils to any depth. It is not unusual with alfalfa to apply 6 inches of water, or over 680 tons

per acre, at a single irrigation, but with the usual field crops it is probable that 3 acre-inches at an application is more usual than a larger quantity. Experience of irrigators generally favors the application of enough water to moisten the soil to a considerable depth, say 1½ to 2½ feet, and then by cultivation producing a mulch of fine soil on the surface to retard evaporation, thus retaining the water of a single irrigation for the use of the deeper roots of the plants for a considerable period, rather than the more frequent application of small quantities, which, by moistening only that portion of the soil very near to the surface, encourages the growth of roots in that portion of the soil which soon becomes dry. Such irrigation leads to spasmodic and irregular growth and often to serious injury to the plant from drought, even though very frequently watered. For general purposes it is undoubtedly the best plan to have the subsoil well moistened early in the season and to keep up the supply of moisture by such copious subsequent irrigation as will encourage the development of deep roots and maintain the uniform maximum growth of the plants.

A convenient figure in estimating the quantity of water to be applied to orchard and ordinary crops at a single irrigation is 100,000 gallons per acre. This will allow of some loss by seepage in the ditches, and usually moistens the soil to a good depth if judiciously applied, and can by the furrow system generally be so applied as to leave the soil in good condition for growth.

The quantity of land which may be irrigated by a single man in a given time is exceedingly variable, and depends greatly upon the skill with which the land has been graded and the ditches have been laid out and constructed. Twenty acres per day may be as easily irrigated under some conditions as 1 or 2 acres under other conditions. In garden operations, of course, the areas covered are usually much less than in the big fields, and a man may sometimes spend a whole day on very much less than an acre and have no reason to chide himself for inefficiency.

WINTER IRRIGATION.

On the plains the winter and early spring months are usually dry, and the soil is sometimes almost as devoid of moisture at the opening of spring as during subsequent droughts. This powdery soil is easily worked, and some have thought it in favorable condition for the reception of seed, and that copious watering later would be sufficient to insure the full benefit of irrigation. But disappointments have sometimes resulted, scarcely better crops being realized than where no water was applied artificially. On the other hand, where similar soil has been thoroughly moistened by the late winter or early spring rains, or by winter irrigation, the fertility of the soil has been amply demonstrated. Whatever may be the explanation of the fact, it has been

found by nearly all observant irrigators of the plains that winter irrigation, thoroughly done, serves very well the double process of fertilizing and moistening. Mr. Perry states that after his eight years of extensive experience in irrigation, he has had the best average results where he has thoroughly saturated the soil to a depth of 2 or 3 feet during the fall or winter or very early spring, and then has cultivated his crops on this land without subsequent irrigation. Mr. C. B. Huffman, of Enterprise, Kansas, has found that land thoroughly irrigated and well cultivated during the season of 1895, and afterwards sown in wheat, produced suprisingly well in 1896 without any irrigation after the wheat was sown, while similar land that had not been irrigated gave a very poor yield. The general experience of orchardists favors winter irrigation. Not unlikely, future practice in the application of water will consist in thoroughly wetting the soil during the winter and in such subsequent irrigation as may be found desirable to maintain the maximum growth, the larger quantity of water being applied in the winter, when evaporation is at a minimum.

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1894.

Report on agriculture by irrigation in the western part of the United States at the eleventh census, 1890, by F. H. Newell, 1894, quarto, 283 pp.

Consists of a general description of the condition of irrigation in the United States, the area irrigated, cost of works, their value and profits; also describes the water supply, the value of water, of artesian wells, reservoirs, and other details; then takes up each State and Territory in order, giving a general description of the condition of agriculture by irrigation, and discusses the physical condition and local peculiarities in each county.

Fourteenth Annual Report of the United States Geological Survey, 1892–93, in two parts, Part II, Accompanying papers, 1894, octavo, 597 pp.

Contains papers on potable waters of the eastern United States, by W J McGee; natural mineral waters of the United States, by A. C. Peale; results of stream measurements, by F. H. Newell. Illustrated by maps and diagrams.

1895.

Sixteenth Annual Report of the United States Geological Survey, 1894–95, Part II, Papers of an economic character, 1895, octavo, 598 pp.

Contains a paper on the public lands and their water supply, by F. H. Newell, illustrated by a large map showing the relative extent and location of the vacant public lands; also a report on the water resources of a portion of the Great Plains, by Robert Hay.

A geological reconnoissance of northwestern Wyoming, by George H. Eldridge, 1894, octavo, 72 pp. Bulletin No. 119 of the United States Geological Survey; price, 10 cents.

Contains a description of the geologic structure of portions of the Big Horn Range and Big Horn Basin, especially with reference to the coal fields, and remarks upon the water supply and agricultural possibilities.

Report of progress of the division of hydrography for the calendar year 1893–94, by F. H. Newell, 1895, octavo, 176 pp. Bulletin No. 131 of the United States Geological Survey; price, 15 cents.

Contains results of stream measurements at various points, mainly within the arid region and records of wells in a number of counties in western Nebraska, western Kansas, and eastern Colorado.

1896.

Seventeenth Annual Report of the United States Geological Survey, 1895–96, Part II, Economic geology and hydrography, 1896, octavo, 864 pp.

Contains papers by G. K. Gilbert on the underground water of the Arkansas Valley in eastern Colorado; by Frank Leverett on the water resources of Illinois; and by N. H. Darton on a reconnaissance of the artesian areas of a portion of the Dakotas.

Artesian-well prospects in the Atlantic Coastal Plain region, by N. H. Darton, 1896, octavo, 230 pp., 19 plates. Bulletin No. 138 of the United States Geological Survey; price, 20 cents.

Gives a description of the geologic conditions of the coastal region from Long Island, N. Y., to Georgia, and contains data relating to many of the deep wells.

Report of progress of the division of hydrography for the calendar year 1895, by F. H. Newell, hydrographer in charge, 1896, octavo, 356 pp. Bulletin No. 140 of the United States Geological Survey; price, 25 cents.

Contains a description of the instruments and methods employed in measuring streams and the results of hydrographic investigations in various parts of the United States.

Survey bulletins can be obtained only by prepayment of cost as noted above. Postage stamps, checks, and drafts can not be accepted. Money should be transmitted by postal money order or express order, made payable to the Director of the United States Geological Survey. Correspondence relating to the publications of the Survey should be addressed to **The Director, United States Geological Survey, Washington, D. C.**

WATER-SUPPLY AND IRRIGATION PAPERS.

1. Pumping water for irrigation, by Herbert M. Wilson, 1896.
2. Irrigation near Phoenix, Arizona, by Arthur P. Davis, 1897.
3. Sewage irrigation, by George W. Rafter, 1897.
4. A reconnoissance in southeastern Washington, by Israel C. Russell, 1897.
5. Irrigation practice on the Great Plains, by E. B. Cowgill, 1897.
6. Underground waters of southwestern Kansas, by Erasmus Haworth, 1897.
7. Seepage waters of northern Utah, by Samuel Fortier.
8. Windmills for irrigation, by E. C. Murphy.
9. Irrigation near Greeley, Colorado, by David Boyd.
10. Irrigation in Mesilla Valley, New Mexico, by P. C. Barker.

In addition to the above, there are in various stages of preparation about twenty other papers relating to the measurement of streams, the storage of water, the amount available from underground sources, the efficiency of windmills, the cost of pumping, and other details relating to the methods of utilizing the water resources of the country. Provision has been made for printing these by the following clause in the sundry civil act making appropriations for the year 1896-97:

Provided, That hereafter the reports of the Geological Survey in relation to the gauging of streams and to the methods of utilizing the water resources may be printed in octavo form, not to exceed 100 pages in length and 5,000 copies in number; 1,000 copies of which shall be for the official use of the Geological Survey, 1,500 copies shall be delivered to the Senate, and 2,500 copies shall be delivered to the House of Representatives, for distribution. (Approved, June 11, 1896; Stat. L., vol. 29, p. 453.)

Application for these papers should be made either to members of Congress or to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
Washington, D. C.

54TH CONGRESS, 2d Session. } HOUSE OF REPRESENTATIVES. { DOCUMENT No. 346.

DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 6

UNDERGROUND WATERS OF SOUTHWESTERN KANSAS.—HAWORTH

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

UNDERGROUND WATERS OF SOUTHWESTERN KANSAS

BY

ERASMUS HAWORTH

WASHINGTON

GOVERNMENT PRINTING OFFICE

1897

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, April 9, 1897.

SIR: I have the honor to transmit herewith a paper entitled Underground Waters of Southwestern Kansas, by Erasmus Haworth, geologist of the University Geological Survey of Kansas, and to recommend that it be published as the sixth number of the series of Water-Supply and Irrigation Papers.

The field work upon which this report is based was carried on by Professor Haworth during the summer of 1896 in connection with the investigations of the Division of Hydrography. Its object was to obtain detailed information concerning the amount and quality of the underground waters, in order to throw light upon the problems connected with the utilization of these in the development of agriculture upon the Great Plains. Although the investigations were of necessity confined to a somewhat limited area, the conclusions have a general value in showing the limitation to which similar areas of the public domain are subject.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

UNDERGROUND WATERS OF SOUTHWESTERN KANSAS.

By ERASMUS HAWORTH.

INTRODUCTION.

SOURCE AND DISPOSITION OF WATER.

All terrestrial water comes primarily from the ocean, whence it is taken by evaporation. It may then be carried by the winds to the farthest portions of the dry-land areas and deposited on the surface of the ground, principally as rain, but partially as snow, mist, fog, or dew. No ground water available to man in any portion of our globe has had or can have any other ultimate source, whether we consider the water near the surface or that more deeply buried.

Water thus left upon the dry land deports itself in a variety of ways, dependent upon the different conditions under which it is placed. A large portion is evaporated directly from the surface before it has had an opportunity to run off or to be absorbed by the soil or to penetrate to greater depths. Of that which is absorbed, large portions are ultimately dissipated by evaporation from growing vegetation. A second portion runs from the plains and hillsides down into the streams and rapidly returns to the ocean whence it came, while a smaller portion more gradually works its way into the same streams by seeps and springs and reaches the same destination. Other portions soak into the soil and ground and serve as a permanent supply of moisture in the soils and surface coverings; while still other but lesser parts sink below the surface soils and below the roots of vegetation, where they remain a constant source of available water existing in sufficient quantities to more than saturate the ground, and hence become available when drill or spade penetrates it. Each of these several methods of deportment is important to the student of hydrology, and may therefore briefly be considered here.

SURFACE EVAPORATION.

A large but varying proportion of the total rainfall is evaporated from the surface before it has had an opportunity to run off or to be absorbed by the ground. The proportion thus evaporated varies greatly in different parts of the world and under different conditions of season and tillage of the soil. The dry, hot winds, the scorching

rays of sunshine, and often the hot soil itself cause evaporation. Summer seasons and arid climates are most favorable for rapid evaporation. In countries where the rainfall is light, the climate warm, and the soil barren of vegetation the little rainfall that does occur is largely evaporated, but in the lowlands adjacent to large bodies of water in cool climates, where the precipitation is abundant, the evaporation is very light. The character of soil and soil covering also has a great influence upon the rate of evaporation. A mulch of any character whatever greatly retards the evaporating action. In cultivated fields a thin mulch of dust or of straw or other litter has this retarding influence, making the condition of tilth an important factor in determining the extent of evaporation.

RUN-OFF.

The water which flows from the plains and hillsides down into the streams has been called the "run-off." The percentage of total precipitation thus disposed of depends upon a number of conditions, such as aridity of climate, amount of moisture already in the soil, rapidity of precipitation, and the general character of the ground upon which the precipitation falls.

Other conditions being equal, the drier the soil the greater its absorptive powers. An ordinary rain falling upon a dry, cultivated field will be almost entirely absorbed; but if the ground is already charged with moisture nearly all the rain will run off the surface and be carried away through the ordinary drainage channels. The per cent of the total rainfall which joins the run-off in humid climates is therefore much greater than in arid climates unless other conditions modify the results. In general, therefore, the proportion of the total rainfall which may be counted on for filling reservoirs in arid and semiarid climates is much less than in humid climates.

The rapidity of precipitation is an important factor in the calculation of the relative percentages of rainfall and run-off. A mild rain continued through many hours will give but little run-off, while the same amount falling in a fourth or an eighth the time will give a greatly increased run-off. Unfortunately the climatic conditions are such in nearly all the arid portions of the world that what little rain does fall comes in the form of hard, driving storms. On the Great Plains of America it is by no means unusual for a 2-inch rain to fall in as many hours, while instances are of yearly occurrence in which 4 inches or more falls within one hour. Under such conditions almost all the water runs off, except in the most sandy places.

The most important of all the conditions named affecting the run-off is the character of the ground upon which the water falls. A loose, porous soil will absorb a large portion of a rainfall, as will also a sandy soil, while a close, compact soil sheds the greater part of it. Here the geologic conditions of a country become important. An

area composed principally of a close-grained shale, and a soil resulting therefrom, which generally has a compact clay subsoil, has inferior absorptive properties, while one composed principally of sandstone and sand will let but little water run away.

The flood plains of rivers frequently have little power of absorption. In times of overflow a thin layer of a fine-grained sediment is deposited, which is partially cemented by an organic mucilage produced by the decomposition of organic matter of one kind or another. This material is almost entirely impervious to water, a thin layer of it being sufficient to prevent downward percolation, no matter how sandy the soil is below. Illustrations of such conditions may be found in many places along the valleys of the Arkansas River, the Rio Grande, and other streams, particularly those which rise at high elevations and have a strong velocity throughout their upper course and a low velocity farther downstream.

In times of freshet the muddy water drawn from the streams into irrigation ditches always deposits a film of sediment over the bottom of the ditch, provided its fall is not too great. This fills the little spaces between the grains of sand in the soil and renders the ditch water-tight. Likewise, when such a stream overflows its banks the muddy water deposits a corresponding film of fine mud over nearly the whole of the valley covered by the water, a filling-in process which, continued from century to century, forms an important part of the alluvial soils of the valley. Along the Arkansas Valley such an accumulation of silt has produced beds varying from 1 to 6 or more feet in thickness, a covering that will scarcely let water pass through it until it is loosened by cultivation. The common method of making reservoirs in the valley is based upon the impermeability of the soil to water, and such reservoirs require much less puddling to make them water-tight than those in localities where more sand is present in the soil.

Along the Rio Grande the well-known adobe soils are of the same general character. The adobe is a thin covering, generally from 1 to 3 feet thick, along the river flood plain, resting upon a mass of sand or sandy soil. A pool of water in such an adobe soil will remain in place until evaporated; but should a hole be made through the adobe covering into the sand below, the water will quickly sink.

Many of the upland areas in different parts of the world were at one time the flood plains of rivers, and were more or less covered with such fine sediments, and now constitute close-grained, compact soils, allowing but a small amount of water to penetrate them. Wind action, too, often helps to produce an impervious soil by blowing the finer particles of dust away from some localities and lodging them in others. Generally there is a compensating action here, for the coarser materials left behind form a covering with a high degree of absorptive power, and therefore decrease the amount of run-off.

SOIL MOISTURE.

A portion of the rainfall is consumed in keeping the soil moist. The ground can yield no water unless a portion of it is more than moist. It is not the amount of water a soil or stratum holds that is important, but the amount it will give up when penetrated. In recent years considerable work has been done in determining the capacity of different soils to hold moisture. This is an important investigation in connection with agriculture, and in calculating the percentage of run-off, but in connection with the problem of available underground water supply it is of less value, because it does not show the proportion of water that will be given up when the materials are punctured by the drill. In fact, the best character of ground for producing a good water supply is one which will not admit of a high percentage of soil moisture, but rather a soil that will readily yield almost all its moisture to the general water reservoir below. A sandy soil or a loose, open sandstone will gather large quantities of water from the rainfall and pass it down to the reservoirs below, where it is held available, while a soil with a greater capacity for holding moisture will yield less to the pump.

AVAILABLE GROUND WATER.

Throughout the humid regions of the world, with few exceptions, water can be found everywhere within a few feet of the surface, so that it is the common experience to obtain water for domestic uses by digging from 5 to 100 feet. This condition is so common that the masses of mankind throughout the humid areas of the world have come to look upon it as certain, and rarely give it any special consideration, and the industries and operations of civilized man are based upon a belief in the perpetual continuance of such condition.

The available ground water in all localities and under all circumstances is the residue of the rainfall after the portions mentioned above—the evaporation, the run-off, and the soil moisture—have been deducted. Each of them must be supplied, in whole or in part, before any available ground water can exist. In many places there is an underground movement, so that the available water under a given area may have fallen only in part as rain upon the surface at that place; yet somewhere and sometime it must have fallen as rain, some of which was evaporated, some carried off by the drainage, some held as soil moisture, and the remainder sunk below the surface, below the reach of growing plants, and held in an underground reservoir, inviting the spade or the drill to discover it and the pump to lift it to the surface. But even yet the wastes are not satisfied, for portions of this underground water are carried by underground drainage to the surfaces of ravines and bluffs, bursting forth as springs, and thus joining the general body of the run-off.

GEOLOGIC CONDITIONS GOVERNING GROUND WATER.

The stratified rocks of the earth are a heterogeneous mass of matter arranged in layers one above another. The strata are not coextensive with the surface of the earth, but some of them occur at one place and others at other places, each lapping under or over its neighbor, quite like shingles on a roof. Some of the strata are composed of loose, porous material, such as sandstone or badly fractured limestone, so that water can readily pass through them. Others are formed from the accumulation of finer sediments, such as clay and the finest of silt, while still other parts of the earth are composed of the crystalline rocks, such as granite, porphyry, and syenite. No substance known forming a constituent part of the earth is entirely impervious to water. The solid granite and the compact limestone and marble alike have moisture within them, commonly called "quarry sap," showing that water penetrates them. Compact, plastic clay is perhaps about as good a nonconductor of water as is known, while beds of sand and gravel are at the opposite extreme, allowing water to pass through them with relatively little resistance. The surface of the ground almost everywhere has a covering of residual soils, sands, and clays, varying from a few inches to many feet in thickness. This usually has high absorptive power for water, so that a large amount is received from the rains as they fall.

When the surface water comes in contact with the porous strata it is absorbed and immediately begins moving downward, or as nearly in that direction as possible. Sooner or later it comes in contact with an impervious stratum below, and thereafter can only move laterally down the incline of that surface. The rapidity of motion will now depend principally upon two conditions—the angle of inclination of the impervious surface and the degree of porosity of the material through which the water moves. Should this be a mass of gravel or sand or porous sandstone, the motion will be sufficient to be easily detected, and somewhere farther down the water will reappear as springs or seeps, supplying the streams with "living" water. It matters not whether this porous stratum is on the surface of the ground in the form of a soil covering or whether it is deeply buried by impervious layers, the water movement within it will be practically the same. When the latter condition prevails and a sufficient head is produced, a well drilled through the upper and impervious layers allows the water to rise through the drill hole, and an artesian well results. Where the porous layer is on the surface, as is often the case on the Great Plains, no pressure or head can be produced, for the water is simply running down an inclined surface with nothing above to prevent it from rising, so that it would be comparable to water flowing down a wide open trough.

A good illustration of this latter condition is found near the University of Kansas, at Lawrence. In 1893 the university authorities

decided to own their own water supply. An investigation was therefore made to ascertain whether a sufficient supply could be had within a reasonable distance of the buildings. It was found that on the south side of the hill a large amount of débris produced by the decomposition of the limestone and shales of the hill had accumulated on the hillside, and that it was well charged with water. Fig. 1, drawn to scale, shows the conditions. The hill is composed principally of a fine-grained impervious shale, with a limestone mass (A) on top. At the boiler house, 300 feet south of the brow of the hill, the débris was found to be 40 feet deep. A well dug here (B) during the driest part of a dry year showed that the amount of water was not very considerable. At points farther down the hillside the water was more abundant. Finally, a large well was put down at the point C, 1,000 feet south of the brow of the hill, and galleries about 6 feet in height were run both east and west, just on top of the undecomposed shale, to intercept the

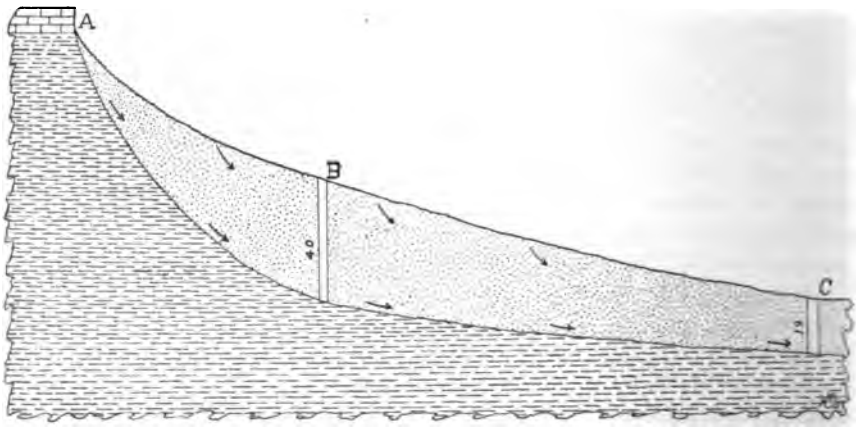


FIG. 1.—Diagrammatic section of hill at Lawrence, Kansas.

water as it moved down the slope and drain it into the well. It was reasoned that this greater distance from the summit of the hill was necessary because the gathering area above the boiler house was so limited that an insufficient amount of water would be obtained at that point, but that with the added distance to where the well was finally located a gathering area of sufficient extent was passed, considering that the average rainfall at Lawrence is a little more than 35 inches annually. Southward the thickness of the débris gradually decreases, so that a mile away it is only an ordinary soil above the undecomposed shale. Were the débris a mass of coarse sand, similar to that so often found in the western part of the State, without doubt the water would soon all run down the hillside and appear as springs in many places; but the débris from a mass of shale is principally a clay, which lets the water through it very slowly, and therefore its southward movement is so slow that little reaches the extreme southern limit of the débris.

Yet in the vicinity of the well a water supply is found sufficient to produce 5,000 gallons a day almost all the year, and 10,000 in wet weather, an amount which could be increased indefinitely by extending the east-west galleries.

Here we have a good illustration of the underground water plane having a very concave surface facing upward. Instead of the water lying in the form of an underground lake, with a level surface, it is a mass of water held in the clay in such a manner that its upper surface is nearly parallel with the highly inclined surface of the ground. We may speak of the clay within the body of water as being more than saturated, using the term saturated to mean holding a water content just equal to the largest amount the clay can hold without being compelled to give up a part of it whenever an opening is made into it. When the clay is in this condition and more water is added to it, this extra amount will run out into the opening made.

As the well at the point C was being dug it was noticed that the clay was moist almost from the surface, but that no water came into the well until it had reached to within about 6 feet of the undecomposed shale. Here the point of saturation was reached, and any greater depth passed clay which was more than saturated, that is, had more water within it than it could hold back from running into the well. This extra amount in excess of saturation is the available water in all cases. It is that which has an underground movement, and which is available in so many parts of the world as supply for man.

In the area under consideration, in the western part of Kansas, we find conditions remarkably similar to those just described for Lawrence. We have a broad expanse of country on which rain falls, and has been falling since the close of Tertiary time, and possibly longer. The surface of the ground is usually well adapted for the absorption of large amounts of this rainfall. After absorption the water obeys the laws of gravity and moves downward, except such portions as are used by the growing vegetation and for moistening the soil. The remainder continues downward until it meets with a stratum which is so nearly impervious that it is almost entirely arrested, after which it moves slowly along the upper surface of the impervious floor in a manner similar to the water in the clays at Lawrence. This floor lies at varying depths in different parts of the Great Plains area, sometimes so deep that the upper surface of saturation can not be reached within 200 feet, while at other places it comes entirely to the surface of the ground.

LOCATING GROUND WATER.

The ability to locate ground water is a qualification desired by many and possessed by few who do not understand the principles governing ground-water movement. The "open sesame" of mythical times gave way to the wand of the wizard, an instrument still

employed in many parts of the civilized world, usually in the form of a forked twig from the bough of a tree, but occasionally a branch, forked or otherwise, from the bough of some particular tree or shrub. In a majority of cases, predictions in humid climates made by the use of the wand prove to be correct unless impervious material is met with in digging, for the whole ground is more or less saturated with water.

As above stated, the water which falls as rain or snow is partially absorbed by the surface materials and starts on its downward course under the influence of gravity. The laws governing its movements are identical with those which govern the movement of surface water. When impervious material is reached the water is arrested in its movements unless it can pass down an inclined plane, the surface of the impervious mass. If limestone or granite or other solid rock is reached, the water will follow the fissures in the rock, and will often ultimately be brought to the surface as springs along ravines and hillsides.

The proper way of considering the matter is to look upon the whole of the subsurface part of the ground as containing available water except where impervious materials exist. If a heavy bed of shale is found which is close-grained and compact, it is useless to look for water within it. Many examples are met with in mining operations which illustrate this, a few of which may be cited. In mining for rock salt at Lyons, Kansas, a mass of loose surface material was found to extend downward for nearly 300 feet. This was so thoroughly charged with water, particularly near the bottom, that it interfered seriously with the mining. Below this a bed of fine-grained Permian shale was reached, in which the salt is found. This shale is particularly impervious to water, as is shown by the fact that no water has come into the shaft since the surface water was shut out, although the shaft is 1,000 feet deep. Similar conditions are found in drilling for oil and gas in Kansas and elsewhere. Often a heavy bed of shale or a solid body of limestone is met which has no water whatever within it. The gas fields of Indiana likewise have similar conditions. Here, after passing through a few hundred feet of water-bearing materials, a 300-foot bed of fine-grained solid shale is found lying immediately over the Trenton gas-bearing limestone. This shale is impervious to water, and lets none of the surface water pass downward through it, and none of the deeper-seated water pass upward. It is so dry that water has to be added while drilling in it.

The existence of such shale beds, or beds of other impervious materials, can generally be recognized by the geologist by surface conditions if he is familiar with a sufficiently wide range of country; otherwise the drill is the only means of discovering it. Wherever large masses of such materials, or of granite or other solid and impervious crystalline rock, cover a wide extent of country, the only hope

of finding ground water is along the ravines and hillsides, where a sufficient amount of surface débris has accumulated to hold the local rainfall, as already explained for Lawrence, Kansas.

Where limestone is the prevailing rock it usually has so many fissures that water finds its way into them and works downward and out through openings along the creeks and bluffs, so that much of it finally joins the run-off. Under such conditions well digging is hazardous, often resulting in failure. It is here that the term "vein" of water is applicable, a term which is generally used indiscriminately, whether the water occurs in veins or in broad beds of water-bearing materials. Here the "water witch" is in most demand.

In such countries careful observation of surface conditions will usually yield good results. The water slowly but surely dissolves the limestone, so that a falling in of the materials above to an appreciable degree is frequently noticed, often resulting ultimately in the production of a ravine of considerable size. The number of fissures along the bluffs will give some idea of the abundance of fissures generally, and therefore of the probability of one being found where a well is desired. But best of all and surest of all in such localities is it to search for places where the surface covering is heavy enough to hold the surface water. Few places in humid climates can be found where this is not sufficient for all ordinary purposes. By far the greater proportion of all the well water and spring water of the world comes from this source. On the great plains of western Kansas the surface covering is generally abundant and heavy, and holds surprisingly large quantities of water. To give a detailed description of the water supply of a limited portion of the plains of Kansas is the object of this paper.

GEOGRAPHY OF THE AREA.

The area discussed in this report is located in southwestern Kansas, and covers 1 degree each of latitude and longitude. It is bounded on the east by the one hundredth meridian west from Greenwich, on the west by the one hundred and first meridian, on the south by the thirty-seventh parallel, and on the north by the thirty-eighth. It includes all of Meade County, nearly all of Seward, Haskell, and Gray counties, about one-third of Ford County, and one-fourth of Finney County. Its eastern limit is approximately the line between ranges 24 and 25 west of the sixth principal meridian, and that on the west side near the middle of range 34. Its south line is about the middle of township 35, and the north line is the line between townships 23 and 24. It is, therefore, approximately 56 by 69 miles square, equal to about 3,864 square miles, or about two and a half million acres. It corresponds to four of the United States Geological Survey quadrangles, known as the Meade, Dodge, and Garden, and the one south of the Garden, not yet surveyed.

The Arkansas River enters this area at the northwest and flows

across it in a southeasterly direction, passing out 16 miles south of the northeast corner. The Cimarron River passes across the southwest corner of the area, leaving the State near the middle of the southern boundary, but flows near the south line throughout the remaining distance to the one hundredth meridian. There is but one other stream of any considerable consequence in the area, Crooked Creek, a stream which rises near the central part and, after meandering in a manner indicated by its name, enters the Cimarron just south of the State line, near the southeast corner of the Meade quadrangle. Aside from these streams, a few lesser ones occur in the northeastern part of the Dodge quadrangle, which drain northeast into the Pawnee—such as Duck Creek, the Sawlog, and the Buckner.

A fair idea of the elevations of the area under consideration may be gained from the following data: The Arkansas River on the east border is 2,460 feet above sea level, and at Sherlock, in the extreme northwestern corner, its level is 2,860 feet, the river making an aggregate fall of 400 feet while crossing the area. The bluffs immediately north of the river at Dodge are 2,600 feet high, while in the extreme northeastern part the elevation is only 2,460 feet, or the same as that of the river at Dodge. The southeastern corner of the Meade quadrangle, near Englewood, has an elevation of 1,960 feet, and the southwest corner of the area, about 4 miles west of Liberal, has an elevation of approximately 2,900 feet. It is therefore a plain, or table-land, with the western edge nearly horizontal, sloping to the east with an average rate of about 7.1 feet per mile along the north end and nearly 17 feet per mile along the south.

The eastern border, therefore, slopes toward the south, making the southeast corner much the lowest part of the whole area. The elevations immediately adjacent to the Arkansas River are greater than can be found either north or south, except those in the southwest corner of the area, where we have higher land than exists along the river.

PHYSIOGRAPHY OF THE AREA.

GENERAL CONDITIONS.

The general physiographic features are those of a broad peneplain sloping gently to the east, into which, at different places, channels have been worn by recent processes of erosion. All the streams with their tributaries, except Arkansas River, appear to be mere channels cut down into the general plain. The Arkansas, on the contrary, throughout the most of its course within this area, seems to be a channel cut into a ridge extending from west to east, as though at one time the river had built its banks higher than the land on either side and had subsequently deepened its channel and produced a flood plain averaging more than 2 miles in width. Both east and west of here the conditions become more nearly normal, as is shown by tributaries entering the river from both sides.

North of the river, where the surface slopes to the northeast, the northeastern drainage often approaches to within a mile and a half of the Arkansas River. The almost complete absence of any tributaries entering the river from the north is remarkable. On the south the conditions in this respect are not quite so extraordinary. A strip of country varying in width from 4 to 18 miles is covered with masses of sand, which have been blown by the winds in recent times into exceedingly irregularly shaped hills and hillocks. Throughout a part of this area tributaries of the river rise from 6 to 10 miles south and work their way through the sand hills to the river. In most instances, even on the south, the drainage toward the southeast approaches surprisingly close to the bluffs on the south side of the Arkansas River.

In the northeast portion of the Dodge quadrangle the drainage is all to the northeast, the waters of which ultimately enter Arkansas River, near Larned, through the Pawnee. As the surface is inclined fully 10 feet to the mile, these little tributaries have cut their channels from 100 to 150 feet deep, and present sometimes almost precipitous bluffs, which bound the narrow flood plains of the different streams.

Over all the southern two-thirds of the area under consideration the drainage is entirely to the southeast. The inclination of the surface in this direction is quite rapid, averaging along the line from Santa Fe through Meade to Englewood more than 16 feet to the mile. The general appearance of the whole country is that of a broad, level plain, with almost no variations of any kind, except here and there where a tributary of the Cimarron or of Crooked Creek has worn its channel downward into the plain. These channels are usually quite narrow, with very rugged bluff lines, produced by the channels being cut to depths of 100 to 150 feet, and in extreme cases to greater depths. When one is standing on the plain the whole country appears to be level, but to one in a valley of a stream the bluff lines are so rugged and so varied that almost a mountainous aspect is presented. This is particularly the case along the Cimarron in the vicinity of Arkalon and along Crooked Creek and its tributaries almost anywhere below Meade.

CIMARRON RIVER VALLEY.

The valley of the Cimarron rarely exceeds 2 miles in width throughout its course across the Meade quadrangle, but it has scarcely passed beyond these limits when it suddenly widens to an unusual extent. Beginning a few miles above Englewood, it has a valley more than 5 miles wide. North of Englewood is a valley, or an area which seems to be a valley of erosion, 10 or 12 miles wide, now covered to varying depths with sand which has a very little silt and soil intermingled. Such a wide valley appearing so suddenly along the course of a stream is very interesting, as its origin is hard to determine. The bluff lines forming the western and northern boundaries correspond remarkably

with those on the south side of the Cimarron. The general appearance of the valley, only a small portion of which is west of the one-hundredth meridian, is that of a valley of erosion, with the sandhills representing the residual sands left behind after the surface drainage had carried away the finer silt and clay.

The Cimarron seems to have reached base-level and to have begun meandering across its flood plain. Beautiful oxbow curves are frequent, and a sluggish nature is everywhere manifest during times of low water. The lesser tributaries usually have deep, narrow valleys, except near where they break through the bluff lines into the Cimarron. Here they often widen into surprising forms, and generally have their flood plains strewn with residual sands retained from the Tertiary beds of sand and clay.

CROOKED CREEK VALLEY AND FAULT.

Crooked Creek, the third largest stream in this area, has some anomalous features which make it interesting. It rises in the eastern part of Haskell County and flows almost due east to near the little village of Wilburn. Here it suddenly turns to the southwest, making an angle of about 60° with itself, to about 20 miles south of Meade, where it bears southeastward to its junction with the Cimarron River. The sharp angle in its course at Wilburn and its southwestern course between Wilburn and Meade, across a country with a maximum inclination to the southeast, are anomalous for a stream in southwestern Kansas. The area in the southeastern part of Meade County is gashed here and there with lesser drainage channels, all of which drain to the southeast in lines approximately parallel with the lower part of Crooked Creek. Some of these lesser channels rise almost on the eastern bank of Crooked Creek, leaving an unaltered table-land along the eastern bank of the creek, often little more than a mile in width, as is well shown on the Meade topographic sheet.

These peculiar physiographic conditions in the vicinity of Crooked Creek, in connection with geological data gathered from wells, led the writer to conclude that local deformation had produced them, and a preliminary notice of the same was published,[1] from which the following extracts may be taken:

The bluff lines along Crooked Creek are quite interesting in character, particularly below Meade. Throughout the portion of its course where it flows east the bluffs on either side of the creek are not especially different from the ordinary. Tributaries from the north are most numerous, but quite a number are found entering the creek from the south in the northwestern part of Meade County. Farther east, opposite the artesian area, no tributaries of any consequence are found on the south, while arroyos of greater or less size are found every mile or two on the north. For 20 miles below the sharp angle at Wilburn scarcely a tributary as much as 2 miles in length enters from the east, while below Meade the drainage streams flowing southeast to the Cimarron rise almost on the verge of the eastern bluffs of Crooked Creek. Throughout this distance many tributaries

[1] Am. Jour. Sci., 4th series, Vol. II, 1896, p. 368.

enter from the west, the most important being Spring Creek, about 12 m and Stump Arroyo, nearly as long.

The general character of the uplands is that of a broad plain inclir southeast about 10 feet to the mile. The various drainage channels are into this plain, generally producing abrupt bluffs on each side. From to Meade, however, the bluffs of Crooked Creek are far apart, with the the artesian area between. Below Meade the bluffs on the east side of are high and abrupt, often being almost precipitous in character. The decidedly new appearance, as though the erosion which produced them modern. Almost none of the rounded forms of old age are to be found angular points and steep walls of recent formation are everywhere pres the western side there is a gently sloping plain stretching from the creel 1 to 5 miles away, producing an appearance scarcely duplicated within t The general upland plain from 8 to 12 miles to the west of Crooked C physiographically and geologically corresponds with the plain on the ea creek, which approaches to within less than a quarter of a mile of the c ley. The general appearance from Meade southward is that of a fault, western wall dropped and Crooked Creek occupying a position over the f Northward the whole artesian valley seems to have been dropped do leaving an abrupt wall on the west and a more gentle wall on the east. anywhere in the valley, one can see the wall all around. On the west siderably over 100 feet in height, while to the east it is somewhat less, very perceptible. We have here a valley occupying about 60 square mil is so different from anything else known in this part of the country t exceedingly difficult to explain its origin by attributing it to erosion. The position of the creek is likewise hard to explain by ordinary erosion. T angle at Wilburn and the southwestern direction for nearly 20 miles plain sloping to the southeast are certainly very remarkable, and proba a cause different from that which ordinarily determines the location and of streams. But if in post-Tertiary times a triangular area equaling in position the present artesian area could have dropped 100 feet or more single fault line extending southward to beyond the limits of Kansas, changing the direction of Crooked Creek into the present channel below V the general physiographic conditions could easily be accounted for.

It should be added that there is a chain of wet-weather lakes reaching e from Wilburn to the north of Minneola which may represent the former of the eastward extension of Crooked Creek. An examination of the lends more color to this view than can be gained from the United Stat graphic sheets, for 20-foot contour lines often fail to represent physic conditions of great importance in such studies as these.

Along the upper part of Crooked Creek, from a few miles Wilburn, the general conditions are those of a stream that has reached base-level. In the artesian area and at all points bel creek has a valley of considerable width and the general appe of a stream which has long ago reached its base-level. The nu ox-bow curves, due to the migration of the channel, are every present. In addition to this, it is generally found that it has b its banks until they are higher than the adjacent valleys. This to a perceptible degree almost entirely through the artesian vall is also true, but to a less extent, in the valley below Meade.

The general uplands of the area under consideration have the a ance of a broad peneplain which has been so elevated that a n of flood plains is now being produced along the various channel

the western part the inclination of the surface is uniform and gentle, and but few channels of any description are found. The rapid inclination of the surface to the southeast throughout nearly all Meade County and the southern part of Seward County gives so great a fall to the streams that their erosive action is more pronounced, and consequently the surface has been changed to greater depth and a corresponding rugged topography produced. The rainfall is so meager that few of the streams have water in them as much as a quarter of the year. Those which have worn their channels deep enough to come into contact with the general underflow water have springs and seeps in great abundance along them, and pools of living water throughout the entire year. This wearing down probably has occurred, however, since the main part of the erosion was done, and consequently has exerted but a limited influence on the general physiographic features.

SAND DUNES.

One of the interesting topographic features frequently observed is that produced by the sand hills or sand dunes. On the south side of the Arkansas, throughout its entire length in this area, a strip of country varying from 4 to as much as 15 or 18 miles in width is covered by loose sand which has been blown by the winds into the hills and hummocks so common in sandy countries. The area is exceedingly irregular in its southern boundary. In some places it is not more than 3 or 4 miles across, while in others the distance is much greater. Near the western side of the Garden quadrangle the sand hills reach southward from the river almost uninterruptedly to within Haskell County, a distance of from 18 to 20 miles. Immediately south of Garden the sand hills extend only about 7 or 8 miles, where a strip of country is reached on which there is but little sand. But farther east, through the eastern tier of townships in Haskell County and Finney County, another southern projection of the sand hills area reaches from 12 to 15 miles south of the river. Still farther east, in Gray County, south of Ingalls and Cimarron, the sands likewise extend from 12 to 18 miles south of the river, or to within 5 or 6 miles of Montezuma. East of this area again, throughout the remainder of the Dodge quadrangle, the sand hills area gradually contracts in width, so that immediately south of Dodge it is only 4 or 5 miles in width. The extent and location of the sand hills are well represented on the topographic sheets of the United States Geological Survey.

In most places, both north and south of the river, outside of the area of river sand hills, relatively little sand is found on the uplands. In the vicinity of Wilburn and Fowler, however, east of Crooked Creek, an area of sand hills exists, covering 50 square miles or more, which has a general appearance similar to that of the river sand hills area. The character of the sand is practically the same, and in most respects the conditions south of the Arkansas River are duplicated.

Again, in the southeast part of Meade County, in the broad Cimarron Valley to the north of Englewood, an area of from 12 to 18 miles in width is covered with sand dunes which are practically the same as those on the south side of the Arkansas. The whole face of the country here for many miles up and down the Cimarron River, except some irregularly shaped areas, is covered with the sand. The exceptions referred to are peculiar and interesting. The greater part of the valley occupied by Colonel Perry's ranch has but few sand hills. Here we have an area 4 or 5 miles across, lying between the sand hills proper and the Cimarron River, the general character of whose soil is that of the alluvial soil common to the flood plains of rivers. Farther down the river to the east the sand hills approach almost to the river bank.

To the north of Englewood, where the sand hills are best developed, a portion of which territory lies within the Meade quadrangle, the sand practically covers the whole face of the country. It is blown into hills and valleys, irregular in outline and position, with no apparent indication of the directions from which the principal winds came. Here and there the sand is still blowing, producing barefaced hills with no vegetable covering, showing that the movement is still in progress. The greater part of the surface, however, is well covered with vegetation, which implies a cessation of the sand movement. The principal sand dunes seem to be residual in character—masses of sand left behind after the finer parts have been carried away by wind and water. For a fuller treatment of this subject the reader is referred to a discussion of the Physical Properties of the Tertiary, by the writer, in Volume II, University Geological Survey of Kansas.

PECULIAR ARROYO EROSION.

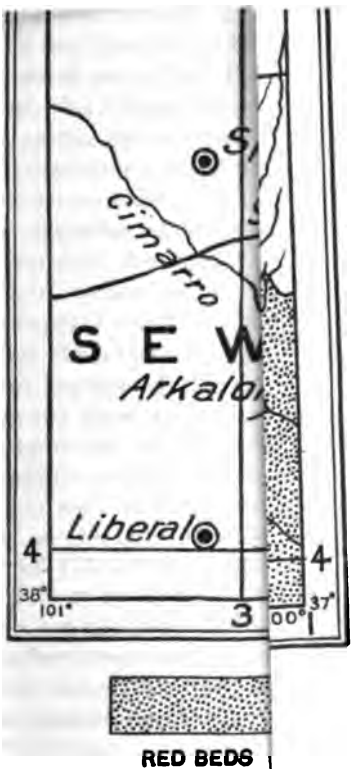
A peculiar form of valley erosion is noticed throughout western Kansas, a form thus far unobserved elsewhere by the writer, and one upon which no literature seems to exist. The lesser tributaries to the principal drainage channels in their uppermost course frequently are quite void of water almost the entire year. As a result of this, buffalo grass or blue stem entirely covers the bottom of the arroyos. Such arroyos usually are from 50 to 200 feet in width, even to their very sources. The peculiar and characteristic feature of such arroyos is the shape of the bank at the margins. In almost all instances over the whole western part of Kansas such arroyos have a vertical wall at the outside part of the bank, varying in height from 2 to 3 feet to a minimum of only a few inches. The whole bottom of the arroyo is, as a rule, covered with grass, and seems to have no corrasion marks along it. But on the outer borders the arroyo is separated from the main upland plain by the vertical wall. This feature is sometimes noted to a limited extent along the little sink holes which are so abundant in this part of the country. Some of these depressions,

measuring no more than 10 or 15 feet across, have the buffalo grass growing all over them, and have their walls assuming this vertical character, in every respect similar to the walls of the arroyos.

These interesting features of the physiography of the Tertiary plains seem to have been caused by the underground creeping of the looser sands and clay which are not held together by the grass roots of the sod. As water is so rare in the arroyos, the conditions are as favorable for the growth of vegetation in the bottom of the arroyos themselves as on the uplands. When the rains come, the ground is softened probably more in the arroyos than elsewhere, and is thereby made more easily movable. The existence of the water is of so short a duration that the mechanical action of its flow is not sufficient to corrade the surface. But as the inclination is generally quite steep, and as the water softens the clays and sands, gravity will cause a slow, but constant creeping downstream of the material which is not held in place by the grass roots. In this way the effect is similar to that which would be produced were a blanket spread from bank to bank of the arroyo, a blanket which was not removed or carried away by the drainage, but which would allow the grounds beneath to become softened and creep downstream by the influence of gravity. The blanket in question would move vertically downward as the material beneath it was carried away, and the vertical walls at the outside of the blanket would be maintained, constantly growing higher as the materials from beneath were removed by the downward creeping.

GEOLOGY OF THE AREA.

The general geology of this part of the State is now fairly well known. Excepting a few small portions in the southeast, the whole area is covered with Tertiary sands, gravels, and clays. The lowermost formation is the Red Beds, which are exposed along a few of the bluff lines and in some of the lowest valleys in the extreme southeastern part of the Meade quadrangle. Farther to the east, in Clark County and beyond, the Comanche overlies the Red Beds. This formation thins westward, however, so that only a few feet of the black Comanche shales is found anywhere within the Meade quadrangle, and that in the extreme eastern part. It seems entirely to disappear westward, as no traces of it have been found. Above the Comanche lies the Dakota, a formation consisting largely of sandstone. It is not exposed at the surface anywhere within this area, but has been reached frequently by wells, and is known to exist both to the east and to the west, so we are sure it is spread over the whole of the northern and central parts. The Dakota is followed by the Benton, which is largely a limestone formation consisting of beds of limestone alternating with black shale. It is found exposed at the surface in a few of the arroyos of Crooked Creek and along the Saw-


Cimarro
S E W
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RED BEDS

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log in the northeastern part of the Dodge quadrangle, and it probably underlies the northern part of the Meade quadrangle. Covering the whole of these is the thin mantle of the Tertiary sands and gravels.

RED BEDS.

The Red Beds cover wide areas in south-central Kansas. They occupy the surface over the greater part of Clark, Comanche, and other counties to the east as far as Sumner County. They extend westward into Meade County, and are found at or near the surface over five or six townships in the extreme southeast corner of the Meade quadrangle. The broad valley around Englewood, which reaches northwest almost to Cash City, has the Red Beds for its floor. The Tertiary sands and gravels are irregularly scattered over this valley, in some places as much as 50 or 100 feet thick, while elsewhere the Red Beds are exposed on the surface. They constitute the main mass of the hills and bluffs to the west and northwest of Englewood, but on account of the Tertiary capping of the hills and the Tertiary sands and gravels in the valley below, when represented on the map they appear as narrow strips winding back and forth through the course of the various lesser tributaries, unless, indeed, the thin covering of the Tertiary in the valley should be neglected, and the whole represented as the Red Beds. They are exposed in the bluffs on both sides of the Cimarron at Englewood and on both sides of Crooked Creek as far up as Odee post-office, the farthest northwest exposure known covering a small area on the east bank of Crooked Creek about 3 miles above Odee.

The character of the upper surface of the Red Beds is interesting on account of the great irregularities which it presents. An examination of section 1 of Pl. IV will show that the surface of the country drops rapidly southward from near Minneola, and that the surface of the Red Beds likewise drops, inasmuch as it is about parallel to the general surface of the country. Aside from this rapid inclination southward there are other local irregularities. In the Cimarron Valley, where the whole surface is covered by a layer of the soil and silt from 10 to 15 feet deep on an average, occasional places have been found in well drilling where great depressions exist. At one farmhouse, on the land of Colonel Perry, a well was sunk to the unusual depth of 175 feet without reaching the Red Beds, while less than a half mile away they are exposed almost at the surface. Such irregularities are probably due to surface erosion in pre-Tertiary time.

Another irregularity is present which is probably of a different kind. As just stated, the Red Beds constitute the main part of the bluffs on the eastern bank of Crooked Creek from Odee to its junction with the Cimarron, and on the left bank of the Cimarron a few miles below. On the west bank of Crooked Creek the Red Beds are not found. Neither are they found on the south side of the Cimarron until a point is reached near the mouth of Crooked Creek, or almost in line with

the trend of the lower part of Crooked Creek, when suddenly they appear on the south side of the Cimarron in forms as massive and prominent as those on the north. This remarkable condition of the location of the Red Beds along Crooked Creek has already been referred to in these pages, and has been explained by assuming a fault line to exist along Crooked Creek, with the strata on the western side dropped to an unknown distance, at least 100 or 150 feet.

In constitution the Red Beds differ from anything else known in Kansas in a few important respects. Their bright color is their most striking characteristic. Wherever they are found they are readily recognized by this feature. No samples of them have yet been analyzed to determine their chemical composition, but it is evident that their brilliant color is due to the presence of large quantities of red oxide of iron intimately intermixed through the whole mass. They vary considerably from place to place, but seem to be composed entirely of clay and sand, very imperfectly bedded, but always colored with red iron oxide. In places far to the east we find beds of sandstone sufficiently cemented to form a low-grade building stone. Elsewhere the sands are entirely wanting. Many samples of the red clay have been examined which apparently contained not even traces of the fine sand.

Gypsum is another constituent, which assumes great prominence in the vicinity of Medicine Lodge and farther to the west. It seems to be well stratified in the vicinity of Medicine Lodge, forming heavy layers from 5 to 10 feet in thickness. These strata have a lateral extent of many miles, and have been important agents in the production of the peculiar and varied physiography for which portions of Barber and Comanche counties are noted. Gypsum has also been formed in many fissures, large or small, which cut the Red Beds in various places. These forms of gypsum are secondary in origin, and seem to have been deposited by infiltrating water probably long after the Red Beds themselves were lifted into dry land.

Salt is likewise scattered irregularly through the Red Beds. It is leached out by the water and is deposited along the salt marshes so common in the Cimarron River Valley to the south of the State line. Probably the salt is irregularly disseminated throughout the material; possibly heavy deposits of rock salt may yet be found beneath the surface, although no positive indication of such has yet been observed. It is certain, however, that in some way, while the Red Beds were forming, conditions were favorable for the accumulation of salt to so great an extent that in the aggregate the amount deposited is very considerable.

Thus far no fossils of any kind have been found anywhere in the Red Beds within this State. Those of Texas have yielded fossils of Permian character, and it is probable that they are of the same age as those of Kansas, although they have not yet been positively shown

to be connected. Little true stratification can be noted in the Red Beds in places where their principal component is clay, but when sand becomes more abundant, so as to form a sandstone, the bedding planes are more strongly marked. In the southeastern part of the Meade quadrangle, immediately at the summit of the Red Beds, is a tolerably well defined sandstone from 3 to 6 feet in thickness, called the Basin sandstone, on account of its being so prominent in the walls around the great basin in Clark County. At the southwesternmost exposure of the Red Beds at Odee this sandstone seems to be wanting, while the clay composing them is so entirely free from sand that no grit can be detected by the teeth.

This absence of local stratification is almost lost sight of when we contemplate the Red Beds as covering wide areas. They form a marked horizon between the Comanche or Dakota above and the black shales and buff limestone of the Permian below. Through all western Kansas they incline to the east or northeast or southeast, as is well shown by noting on the map their elevations at different places where found. Where exposed at Odee they have an elevation of nearly 2,400 feet, while in the bluffs near Englewood, in places where we know the measurements are made on the uneroded upper surface, their elevation is but little more than 2,100 feet, making a dip of the upper surface to the east of fully 250 feet in a distance of 15 miles, or an average of near 17 feet to the mile. The same Red Beds were reached in a deep well at Santa Fe years ago at an elevation considerably greater than where they are exposed at Odee, showing that as they extend westward their upper surface rises.

The origin of the Red Beds is pretty well indicated by their character. The large amount of iron oxide, of gypsum, and of salt which they contain, and the total absence of fossils, imply that they are the result of the accumulation of sediment in a concentrated ocean water. Many characteristics of the formations in central Kansas in the Upper Permian point to the existence of an inland ocean which was evaporating more rapidly than it was filling from surface drainage, thus producing a stronger and stronger brine. The large deposits of rock salt in what has heretofore been called the Upper Permian—the salt beds supplying the mines at Hutchinson, Lyons, and other places in the south-central part of Kansas—have probably been formed by the desiccation of an inland ocean. The dark-colored shale which is embedded with the salt in these places likewise implies that sufficient organic matter, either from sea or land, was accumulated with the earthy masses which constitute the shale to give them their black color. As time passed the accumulation of organic matter from all sources was finally prevented. As a result, the surface oxidation of the iron compounds leached from the adjacent land was carried on to an extent sufficient to produce the red color in the sands and clays of the Red Beds.

An important lesson may be gathered from these considerations by one studying the water problem in western Kansas. Should a well penetrate the Red Beds, their fine-grained, compact, argillaceous character makes it extremely doubtful whether water in any considerable quantity can be obtained from them; and still worse, should water be obtained it is almost certain to be so mineralized with salt and gypsum and other soluble products that it will be entirely unsuited for either domestic purposes or for irrigation. Therefore, should anyone when using the drill in the search for water anywhere in the southwestern part of the State penetrate the Red Beds, he should immediately discontinue boring, lest he spoil the character of the water he may have already obtained.

DAKOTA.

The Dakota formation underlies about three-fourths of the area covered by this report. Its position is well shown in the accompanying geologic sections (Pl. IV, p. 42). From these it will be seen that it gradually thickens to the north and thins southward until it entirely disappears. The southeastern limits of the Dakota can not be outlined in detail on account of the heavy mantle of Tertiary which conceals it from view in most places.

In character the Dakota is largely a sandstone formation, so much so, indeed, that it is frequently spoken of as the Dakota sandstone. Every deep well which has penetrated it in southwestern Kansas shows that shales are embedded with the sandstone. The extent of these shale deposits is not known, for nowhere can we find any exposure of the Dakota at the surface. Farther east, in other parts of Kansas where they come to the surface, it is seen that a considerable proportion of the thickness—probably more than half—is shale of some kind. In most places where exposed at the surface in Kansas the sandstone is colored brownish red by iron oxide, and in some places in this area the drill has brought up the same brownish-colored sand. Farther west in Kansas and Colorado the brown color is not so prominent.

The Dakota formation has an unusually great extension. It reaches from the Dakotas southward into Texas, and probably beyond; from central Kansas westward to the "Hogback," near the eastern foothills of the Rocky Mountains, and northwestward into Montana and Wyoming. As a sandstone it is characterized by great uniformity of texture and a small amount of cementing material to bind the grains together. The latter property makes it an open and porous rock, so that it can serve as a great underground reservoir capable of holding a high percentage of water or of allowing a relatively free transmission of water from one place to another within it. Westward from Kansas it is found sometimes at the surface, where it can absorb the rainfall, sometimes in contact with the Tertiary, so that the under-

ground water of that formation mingles with its own, and sometimes buried beneath the Benton and higher Cretaceous formations. It seems to have an unbroken continuity from its exposure in Kansas westward almost to the mountains, throughout which distance it has an average dip to the east of from 5 to 8 feet to the mile. It is, therefore, a most important formation to anyone studying the water problem in Kansas, and will be recalled for a further discussion later in this report.

BENTON.

Above the Dakota lies the Benton, a formation composed of alternating beds of limestone and black or dark-colored shale. The proportion of shale to limestone is probably about as 1 to 4 or 5. The limestone is generally a light buff in color, sometimes inclined to a bluish hue on unweathered surfaces. It is usually much softer than ordinary limestone, but fragments exposed at the surface show perceptible hardening. It always contains large quantities of fossil shells.

The Benton formation is exposed at the surface in the northeastern part of the Dodge quadrangle along Sawlog Creek and some of its deeper tributaries. It is again exposed over small areas in places along the northern tributaries of Crooked Creek in the southern part of Gray County. Aside from these two limited areas it is entirely concealed from view by the overlying Tertiary sands and clays. However, we know from the records of different wells and from its occurrence elsewhere that it underlies the Tertiary formations over the whole of the northern part of this area, reaching southward to the banks of Crooked Creek, and probably farther on the western side.

Many wells reached it at different places in township 29, in the southern part of Gray and Ford counties, some of which penetrated it 150 feet and more without passing through it, while others, farther east and south, proved that its thickness there was much less. The city well at Santa Fe is reported to have found but 13 feet of the Benton limestone. It would seem, therefore, that there is a considerable thickening east from Santa Fe, as shown in the geologic section.

Farther west, in the vicinity of Hartland, Kendall, Syracuse, and Coolidge, the Benton is exposed in the bluffs along the north bank of the Arkansas River, furnishing a limestone which is quarried at different places. There is little room to doubt, therefore, that the Benton underlies the whole of the area north from the southern limits along Crooked Creek to Santa Fe, as already described.

Neither the Benton limestones nor shales are water bearing. Not a single well has yet been drilled in the shales which found water in them. The limestone is a fine-grained mass, capable of holding or transmitting but little water, while the shales are so close and compact that they are entirely incapable of permitting any considerable quantity of water to pass through them. The Benton, therefore,

furnishes a floor impervious to the water of the overlying Tertiary sands, a floor preventing the Tertiary ground water from passing downward and the water of the Dakota sandstone from passing upward.

TERTIARY.

The Tertiary formations in Kansas are composed principally of gravel, sand, black sand, clay, and silt, with a small amount of material usually called "volcanic ash." These materials are mixed together in an irregular manner, so that the same relation does not exist between them in different localities. The gravel consists of pebbles varying in size from 4 or 5 inches in diameter to the finest, grading into sand. They are composed principally of the ordinary rock-forming minerals, and seem to be fragments of granite, syenite, porphyry, andesite, rhyolite, basalt, and not infrequently of pure quartz. Their character leaves little room for doubt that they were carried here from the mountains to the west.

The relative position of the gravel beds is variable. In some places they seem to be near the bottom of the Tertiary; elsewhere they are on the summit of the highest hills. A good example of the latter is found along Spring Creek, in Meade County, about 4 to 8 miles southwest of Meade Center. Here the so-called mortar beds—a mass of gravel and sand cemented with calcium carbonate—cap the top of the highest hills in the country. Some of them have the butte form so common where hills of erosion have a hard covering rock on top of a larger mass of soft material.

The sand is composed of sand grains ranging in size from the ordinary coarse sand which grades into gravel down to the finest of sand. The grains are principally of ordinary quartz, but are usually intimately associated with feldspar particles, confirming the teachings of the gravel regarding their origin. The sand is about as well stratified as the gravels already mentioned. In places beds of sand are found well stratified, while elsewhere it is so intimately mixed with clay or gravel that the formation can hardly be called sand beds.

Almost everywhere in the Tertiary are found small accumulations of black sand, which have been slightly segregated by rain water carrying away the finer materials and leaving these little grains behind. Originally they are intimately mixed with the clay and finer quartz sand. The little rivulets of water on the hillside carry away the lighter particles of clay and silt and let the black sand grains accumulate along the wagon tracks of the country roads and the eddies of the small ravines. These black grains are found to be composed entirely of black oxide of iron, principally magnetite, but partially dark hematite. Doubtless they were original constituents of the crystalline rocks of the mountains to the west. When the rocks were disintegrated by weathering and the débris was transported eastward by water, the iron oxide grains were carried along with the

TERTIARY BLUFF AND SPRING-FED POOL, DUCK CREEK, 5 MILES NORTH OF DODGE, KANSAS.

other material and lodged here and there wherever the current velocities permitted.

The clays and silts vary in character from place to place and at different depths. Occasionally almost pure masses of clay are found, beds almost entirely free from admixtures of sand, clay with a high degree of plasticity and in every respect resembling the purest known, except that it contains sufficient impurities to modify its color. Frequently such masses of clay seem to be colored with decaying organic matter, as though during its accumulation such matter in one form or another was present, at least in limited quantities. Elsewhere the color of the clay seems to indicate the absence of organic matter of any kind.

The stratigraphic property of the clay is interesting. In places it exists in broad layers, apparently extending for miles in unbroken beds. Elsewhere it forms lenticular masses, oblong in horizontal dimensions and irregular in peripheral outlines. Sometimes it is interbedded with the heavy gravel and sand beds, and elsewhere seems to be relatively distinct from them.

Along the Arkansas River Valley, near the bluffs north of Garden City, a heavy bed of clay nearly 100 feet thick extends up and down the valley for 4 or 5 miles. Its north-south diameter is usually about half a mile. South of the river 12 or 15 miles from Garden City is another locality in which occur irregularly shaped clay beds or clay bowlders, as they are locally called. During August, 1896, a well was drilled about three-fourths of a mile south of Atwater, in Meade County. It went to the surprising depth of 288 feet, passing through nothing but a light-blue plastic clay almost the entire depth. Other wells on every side of this one, from 1 to 2 miles away, found the usual amount of water-bearing sand at from 20 to 40 feet. Such illustrations could be multiplied until the whole of the Tertiary of Kansas was covered. Everywhere such irregularities exist. Few wells have been made which did not pass through both sand and clay. Even in the sand hills south of the Arkansas River the few wells dug or bored invariably found clay. The State well in the sand hills just south of Cimarron may be taken as an example. At a depth of 23½ feet a bed of remarkably compact plastic clay was reached, about 5 feet in thickness.

In many places in western Kansas and elsewhere on the plains a small amount of a fine-grained matter is found, which is generally called volcanic ash. A few deposits of the same material have been found in this territory. The best exposure known is along a tributary to Crooked Creek, about three-fourths of a mile west of Meade Center, although other lesser deposits are known in Meade County and elsewhere.

Over a large portion of the whole Tertiary area of the plains the surface is covered with a fine-grained soil which has so high a percentage

of clay within it that it has a relative high plasticity and other properties that have given it the name "Plains marl." It covers more than half of the surface, but by no means all of it. Neither is it confined to the surface, for often the same kind of material is found interbedded between layers of other materials. It is probably composed of the finest silt and clay particles which migrated eastward during Tertiary time and were lodged here and there wherever the conditions of water velocity dictated. In recent times, also, the winds have exerted a sorting action on the surface materials, which has helped to make the Plains marl more characteristic. The strong winds pick up the finest dust and carry it for miles and deposit it wherever a suitable lodging can be secured. This not only concentrates the finest materials together by movement, but also leaves the coarser soils and sands behind, so that the same process produces sand dunes and sandy soils which are often mere residual products after the finer silt has been blown away.

The structural relations of the different Tertiary materials are far from regular. It is doubtful if there can be any definite stratigraphic relations established covering a considerable scope of country. The gravel and sand are frequently cemented into a moderately firm rock by the presence of a variable amount of a calcium carbonate cement. This cement is sometimes found in the clay as well, but it is most abundant in the sand and gravel, producing a sort of sandstone or conglomerate to which the name "mortar beds" or "grit" is generally applied. Some of the varieties of this are the so-called "natural mortar," which is extensively used throughout the West for making a mortar to plaster with and to roof houses. These mortar-bed horizons are prominent features in many places and constitute the only hard and resisting strata in the Tertiary. The idea so frequently expressed, that they are located near the base of the Tertiary, is correct for some localities, but incorrect for others.

Along the Buckner, in the southwestern part of Hodgeman County, the sand and gravel are as firmly cemented as at any place known to the writer. Here they form a tolerably solid rock which lies at the top of the bluffs on the south side of the Buckner. They are in beds from 10 to 20 feet thick, varying much more than ordinary sandstone beds do. Below them in this locality the bluffs are composed of a looser and finer material. At other places along the Sawlog, near by, the mortar beds are found near the bottom of the Tertiary, and not infrequently resting immediately upon the Benton limestone.

The north bluff line of the Arkansas River from some distance below Dodge westward almost to Garden is protected by a well-developed mass of mortar beds. Throughout the most of this distance three distinct layers of mortar beds can be traced, while in other places four or more may be found. They are composed of cemented sand and coarse gravel, and are separated from each other by beds of clay and fine sand. The weathering processes wear away the soft

clay beds more rapidly than the mortar beds, producing a series of narrow terraces along the bluffs similar to those generally observed in places where the limestones and shales alternate with each other, as so frequently occurs in the eastern part of the State.

South of the Arkansas River but little of the mortar-bed material is to be seen until the vicinity of Crooked Creek and the Cimarron is reached. Here we have the same lack of regularity so noticeable elsewhere. The most pronounced form of the mortar beds is often found at the very summit of the bluffs, but by no means always so. In other places they occur midway up the bluff, and not infrequently near the base. The bluffs of Crooked Creek below Meade are good examples of this. On the eastern side of the creek they are very rugged, with frequent instances of mortar beds being well developed, but by no means do they form a constant stratum continuously along the bluff. On the western side the bluff line is not so abrupt, and consequently there is not so good an opportunity for observing the mortar-bed masses. To the southwest of Meade, along the upper portion of Spring Creek, however, some of the hilltops are very distinct, and the erosive forms are significant of hills with a protecting cap of hard material covering softer materials. These can well be studied from the Meade topographic sheet. A few of these hills are particularly noteworthy. On the north bluff of Spring Creek, about 4 miles above Crooked Creek Valley, the mortar beds are found lying at the summit of the hill. The sandy clay underneath is worn away, so that quite frequently the mortar-bed rock projects several feet, forming an overhanging cliff. South of Spring Creek a similar condition obtains. Hill point after hill point stands out in the landscape as a prominent feature, on the top of which a horizontal mass of mortar-bed rock serves as a protection to the soft and easily eroded sandy clays beneath.

Along the Cimarron River from some distance above Arkalon to where the river encounters the Red Beds near Englewood its valley is cut downward into the broad plain to a depth of nearly 200 feet. As one stands on a prominent point on either side of the valley and looks up and down the stream, it is easy to see the line of light-colored mortar beds lying almost at the summit of the bluffs, with the darker colored shales and sands beneath. A more careful examination shows that for many miles along the stream relatively firm rock covers the topmost part of the bluffs, and it is largely to this that the precipitous character so pronounced on either side of the river around Arkalon is due. Beneath the mortar beds are found masses of sandy clay, which constitutes the main mass of the bluffs. At other places, particularly along some of the tributaries of Spring Creek near Meade Center, the mortar beds in a well-developed form are found on low ground more than 100 feet below those capping the hills a mile or so away, with no connection between them.

During the last two years the Kansas State Board of Irrigation has

sunk twenty wells in western Kansas, the greater portion of which are confined to the Tertiary. One of the provisions in the contract for the drilling of each well was that a carefully selected and accurately labeled suite of samples should be preserved and delivered to the board, such samples to be taken with sufficient frequency to accurately represent the character of the material passed through. These samples from the different wells were turned over to the writer by the Board of Irrigation and have been carefully examined. This is the first time it has been possible to examine the Tertiary materials at any considerable depth below the surface, except where they are found along the bluff lines of the various drainage streams. They are therefore of more than ordinary importance, and are worthy of notice in this connection.

It was found that little relation existed between the distance from the surface and the size of the gravel. Gravel beds of a considerable degree of coarseness were frequently found near the surface, and the finest sand and clay and silt were not infrequently found near the base of the Tertiary. There was such an irregularity of position shown with reference to any one material, and such a lack of definite relation between the different kinds of material, that it seemed as though but little if any dependence could be placed in any older classification.

In studying the physical properties of the Tertiary it is necessary to emphasize the statement that the so-called mortar beds are simply the sand and gravel and clay materials cemented usually with calcareous cement. The real stratigraphic conditions probably do not depend upon the presence or absence of cementing material, but rather upon the continuity of beds of like material. A stratum of gravel which is not cemented should be considered as important as though it had chanced to have its individual constituents held together by a cementing material of some kind. Yet in our study of the subject we are usually inclined to erroneously regard the beds which are cemented into a firm rock as more important than softer materials. It has been suggested by the writer that the formation of the cementing material has occurred since the deposition of the beds, and that it represents a process of weathering and desiccation still in progress. The ordinary weathering agents produce calcium carbonate near the surface, which is changed to the acid carbonate by rain water containing carbon dioxide washed from the atmosphere. It is then dissolved and carried downward until the dryness of the ground absorbs the moisture, precipitating thereby the neutral carbonate in whatever position it chances to be. As the beds of gravel and coarse sand more freely permit the passage of water through them than do other materials, naturally there would be a greater deposition of calcium carbonate in such beds.

It is doubtful if there can be any regularity discovered between the beds of the different kinds of Tertiary material in western Kansas. The mortar beds occur at all positions from the base to the summit,

as do also the sands and the clays. It has been found impossible to trace a bed of any one material very far in any direction. The records of the State wells add to this difficulty rather than lessen it. Neither does the assistance of paleontology lessen the difficulty, but rather increases it. In Phillips County the mortar beds contain skeletons of the rhinoceros and other animals, indicating that they should be correlated with the Loup Fork beds of Nebraska, and that they are about the oldest Tertiary beds in Kansas. To the southwest, in Meade County, a mass of conglomerate, which is as typical a mortar bed as can be found, is rich in fossil horses, llamas, elephants, etc., which paleontologists class as Pleistocene fossils. We therefore have the mortar beds with Loup Fork fossils at one place and with Pleistocene fossils in another, not only showing a lack of stratigraphic continuity, but showing that, after all, the so-called Tertiary of the State may be part Tertiary and part Pleistocene.

WATER SUPPLY OF THE AREA.

In the discussion of waters on the Great Plains it is well to bear in mind the different conditions under which water exists and the different classes into which the ground waters may be divided with reference to the geologic character of the materials in which they are found. Geologically we have two great classes of ground waters. One exists in the Dakota sandstones. It probably has a slow movement eastward, has principally been gathered from the rains falling in the eastern part of Colorado and farther to the north over areas where the sandstone is exposed at the surface, and in its eastward movement passes underneath the Benton, Niobrara, and other superior Cretaceous formations, so that in most places it exists under a pressure sufficient to cause it to rise an appreciable distance above the level at which it is found by the drill, giving artesian wells, or wells decidedly artesian in character.

The other water is that which is commonly known as ground water, sheet water, or underflow, as these expressions are understood by the people of western Kansas. It is confined to the Tertiary sands and gravels. It lies immediately above the impervious Cretaceous or Red Bed floor, and is sufficient in quantity to more than saturate the materials in which it exists for a distance above the floor varying from 5 to more than 100 feet. Throughout the greater part of the plains area, therefore, these two classes of water are separated from each other by all of the Benton and higher Cretaceous deposits. In rare cases, however, the Tertiary rests immediately on the Dakota sands, permitting the Tertiary water and the Dakota water to commingle. Could we exhaust the supply of either one to an appreciable degree, the other would doubtless be drawn upon and a movement would be set up from one into the other. Still, for convenience of discussion and clear presentation of the water conditions, it is desirable that the two classes should be discussed separately.

DAKOTA SANDSTONE WATER.

The Dakota formation consists largely of beds of sandstone the grains of which are generally but poorly cemented together, leaving spaces between them which may well serve as receptacles for water. This sandstone, as before stated, underlies the greater part of the plains area from the British possessions on the north to Texas on the south. Throughout this entire distance it extends westward to the mountainous area, lapping upon the foothills along the eastern slope of the Rocky Mountains or capping the ridge generally known as the "Hogback," lying just east of the mountains in Colorado, as has been so well shown by Gilbert in his recent article on water conditions in eastern Colorado.[1] In this vast area are many localities where the Dakota is exposed to the surface, so that it can gather water from the rains and melting snows and occasionally from rivers which pass over it. The water which is absorbed passes eastward or southeastward or northeastward, the direction depending upon the inclination of its strata in different localities.

This great geologic formation is a continuous underground sheet for thousands of miles in extent, and has been imbibing water from the rains and snows perhaps for thousands of centuries. It has thus become a great reservoir filled with water, the leaks from which are known in the form of springs and seeps along its eastern borders in many places where it is brought to the surface, and also along the banks of streams which have cut their channels downward until the Dakota has been reached.

In a general way it may safely be said that all that is necessary to obtain water on the Great Plains is to penetrate to the Dakota sandstone. This proposition, although true in a general way, may not be verified in every instance. It is reasonable to suppose that a rock mass covering so wide an area is not perfectly uniform throughout. Here and there may be areas where the cementing material is more abundant than ordinary, or where the grains of sand are finer, or where the sand beds in their original form had silt and clay intermingled to a sufficient extent to produce a relatively impervious mass. We know, in part, that such conditions obtain at irregular intervals, and that consequently a drill hole made in such a place will yield but little if any water; not because the great Dakota beds were not reached, but because they were reached at a place where the open spaces between the sand grains had been filled with clay or mud or cementing material so that water could scarcely flow through.

Experience in drilling for water in the Dakotas, in Nebraska, in Colorado, and in Kansas abundantly verifies the statement just made, that in a general way one may confidently expect to obtain water in large supplies wherever the drill penetrates the Dakota sandstone.

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[1] The underground water of the Arkansas Valley in eastern Colorado, by Grove Karl Gilbert: Seventeenth Ann. Rept. U. S. Geol. Survey, Part II, 1896, p. 582.

CHARACTER AND OCCURRENCE OF DAKOTA WATER.

The character of the water obtained from the Dakota sandstone is variable. Underground water is pure or is mineralized, according to its opportunities for dissolving soluble mineral salts. Could water be confined continuously in a perfectly pure mass of sand or sandstone which had no soluble materials within it, and into which no soluble salts could be taken by infiltrating waters, its character would always remain pure. But nature rarely accumulates a mass of sand without having at least traces of soluble materials along with it. Few terranes are known anywhere in the world which can permit waters to percolate through them for hundreds of miles without giving up mineral matter to the water somewhere throughout the course. It is so with the Dakota sandstone, yet not universally so. For some reason which has not been determined, water which is lifted from the Dakota at one place may have a greater or less amount of dissolved mineral salts than water obtained from the same sandstone 50 or 100 miles away.

The natural processes by which the impurities are gathered from the rocks by the water are such that it is exceedingly difficult for one to give an approximate statement regarding the character of the water that may be found at any locality, unless one can be guided by the water which has already been found near by. This, likewise, is substantiated by our limited experience in drawing water from the Dakota sandstone. The wells at Rocky Ford, La Junta, and other places in Colorado are all mineralized to a similar extent. The springs which burst forth from the banks of the creeks and rivers near by are likewise mineralized.

In Kansas the few wells which have been drilled in the Dakota sandstone have produced different degrees of mineralized water, differing materially in composition from one another and from many of the wells of Colorado and Dakota. The artesian water at Coolidge, which is a Dakota sandstone water, is relatively fresh, carrying little more than 24 grains of solution to the gallon. It has but little odor of hydrogen sulphide, and is in every way a desirable water for all domestic purposes. Farther north, in the vicinity of Oakley, a well reached the same horizon and likewise obtained water, but this was so heavily charged with common salt and other soluble minerals that it was practically worthless. An artesian well east of Oakley, in Saline County, drawing large quantities of water from the same Dakota sandstone, produces a water which is somewhat different from either of those, but which is so salty that it is of but little value for domestic purposes or for irrigation.

In the vicinity of Ness City, Larned, and other points near the Arkansas Valley, the few wells which have reached the Dakota have uniformly obtained water of a high degree of purity, well suited for domestic purposes. These examples are sufficient to show the varied character of the water obtained from the Dakota sandstone; in some

places the water is of good character, while in others it is highly mineralized.

Thus far but few wells in the special area discussed in this report have penetrated the Dakota sandstone. Not one is known to the writer to have done so north of the middle of the area, and but few to the south. In northeastern Meade County and the southern part of Ford County, four or five different wells are known to have passed through the Benton and reached the Dakota. In every instance the water obtained seems to be very abundant, rises to a height of from

FIG. 2.—Reservoir and windmill pumping water from Dakota sandstone, about 18 miles south of Dodge, Kansas.

50 to 150 feet above where it was first reached, and is of so high a degree of purity that no mineral properties whatever are noticeable to the taste. At Santa Fe, likewise, the city well passed through the Benton into the Dakota and obtained a good supply of water of as high a degree of purity as anyone could desire for domestic purposes. These Dakota waters have not been analyzed, largely because their purity is so apparent that analysis has seemed unnecessary.

By referring to the accompanying map (Pl. I) it will be noticed that the southern limit of the Dakota formation passes from a line near Minneola, on the east, to a point a few miles south of Santa Fe, on the

west. It may confidently be stated that the Dakota sandstone extends northward from this boundary under the whole of the area, and that it is water bearing throughout its whole extent. Therefore, a well put down to a depth sufficient to reach the Dakota sandstone will be supplied with abundance of water.

These predictions are based upon the well-known extension of the Dakota sandstone and its property as a water-bearing formation. The depth to which wells at different places will have to be carried to reach the waters of the Dakota sandstone can only be given approximately. By referring to the different geologic sections on Pl. IV it will be seen that the Dakota deposits to the north lie at a similar angle. Our knowledge of this subject is only fragmentary. A deep well at Garden is reported to have reached the Dakota at a depth of 461 feet. This information is all that was available from that part of the area, and section 3 was based upon it.

North of Dodge the Benton is exposed on the surface. Its thickness at this place is not known, but different wells have passed into it from 100 to 200 feet. Farther south, in southwestern Ford County, the Benton is known to be at least 150 feet thick, while farther to the northeast, where it is exposed at the surface, it is estimated to have a thickness of about 400 feet. From these data it was estimated that its thickness at the northeast corner of the Dodge quadrangle is about 400 feet, and section 1 was drawn accordingly.

The areas lying between sections 1 and 2 and 2 and 3 will have the Dakota at about the same distance from the surface. If, therefore, anyone should desire to estimate the depth he would have to go at any particular place to reach the Dakota sandstone, he could obtain an approximate idea by referring to these sections.

The representations here made should be regarded as only approximations, but the best that can be made with our present knowledge. Should a few wells be drilled north of the Arkansas deep enough to reach the Dakota sandstone, corrections could then be made which would make it possible to estimate the distance below the surface at which the Dakota would be reached over the whole area.

ARTESIAN PROPERTIES OF THE DAKOTA WATER.

The Dakota water in all places has artesian properties to a greater or less degree; that is, the water rises through a varying number of feet from the level at which it is found. At Coolidge different wells, when properly cased, gave a constant flow of from 40 to 50 gallons per minute from a 3-inch well. Farther east, at Syracuse, like wells have reached the Dakota and have produced water, but not one has yet been properly cased to determine whether or not the water would rise to the surface.

Northward, in the vicinity of Ness, where the surface elevation is slightly less than the uplands in the vicinity of Dodge, the waters

from the Dakota sandstone rise to within from 35 to 75 feet of the surface. It is probable that wells of this character could be sunk in the area under discussion in which the water would rise nearly to the surface, and possibly in some instances an artesian flow might be obtained. Yet one should not depend too much upon obtaining an actual flow, for it is doubtful if such would be obtained anywhere except in the lowest ground. There can be no good reason, however, for doubting that the water would rise to a point rarely more than 100 feet below the surface, and in many instances much higher than this.

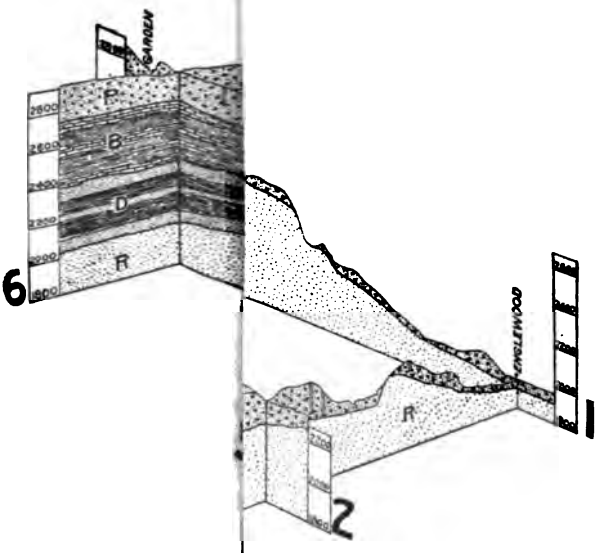
The constant drainage along the eastern borders of the Dakota decreases the water pressure to so great an extent that the height to which it will rise is materially reduced in the Dakotas[1] and Minnesota. The decrease in pressure is frequently as great as 4 feet to the mile near the eastern border of Dakota, a decrease which is attributed largely to leakage. No observation has been made in Kansas to determine the rate of decrease in pressure. Such, in fact, could not be done to any satisfactory degree without a larger number of wells upon which observations could be made.

HOW TO FIND THE DAKOTA SANDSTONE.

Many inquiries have been made by citizens in various parts of Kansas regarding the means by which they could determine how to find the Dakota by boring. As already stated, the whole of the area covered by this report north of the south limit of the Dakota is underlain by the Dakota sandstone. When one drills a well expecting to reach this formation, the Tertiary sands, gravels, and clays will probably first be passed through, and whether or not the Tertiary water is found will depend upon a number of conditions which obtain in the vicinity of the well. Below the Tertiary, limestone and black or dark shale alternating will probably be found. The shale is the material commonly called "soapstone" by the most of the well drillers. In all such cases, as long as the drill is in the shale or limestone the driller should keep on going deeper. Finally the drill will pass through the Benton shales and limestones and enter the Dakota sandstones and clays.

If for any cause or combination of circumstances the desired supply of water is not obtained, he should go deeper, for the Dakota sandstone exists in two or more different layers, separated from each other by clay or shale of varied characters. The only condition which should cause him to stop drilling before the desired amount of water is obtained is that the drill has reached the Red Beds exposed on the surface in the southeast part of Meade County. We do not know how far north these Red Beds extend, but probably they reach far beyond the limits of the territory to which this report pertains. They can be

[1] Preliminary report on artesian waters of a portion of the Dakotas, by N. H. Darton: Seventeenth Ann. Rept. U. S. Geol. Survey, Part II, 1896, p. 666.



TERTIARY

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recognized when reached by the drill in a number of ways. They are generally free from sand, but not always; they are usually slightly salty or in some other way mineralized, so that they may be recognized by the taste; and they have mixed through them small masses of gypsum, a property rarely observed in the Dakota clays or shales lying between the Dakota sandstones. As soon as the driller becomes satisfied that his drill has entered the Red Beds, operations should be stopped immediately. There is no evidence favoring a hope that the Red Beds will produce water in large quantities, while there are many reasons for believing that the small amount which may be obtained from them will be so highly mineralized as to be entirely unfit for use of any kind.

TERTIARY GROUND WATER.

Under this heading are placed the waters drawn from the Tertiary formations. They include all water that may be found in Tertiary sands, gravels, and clays; that is, all available water lying above the uppermost Cretaceous formation. It is the water which is generally known in the West by the terms "underflow" or "sheet water," names which reflect the popular idea regarding the extent and character of the ground water of the plains. The water is found in greatest abundance just above the Red Beds or the Cretaceous floor. The lower portion of the Tertiary sand and gravel is more than saturated, and available water results. The thickness of the water-bearing beds is variable, sometimes being more than 100 feet, and elsewhere being less than 5, but always the water-bearing horizon rests on the impervious Cretaceous or Red Bed floor, or on a like impervious floor of clay.

Almost all the area comprised in this report is underlain by large quantities of water. In the Arkansas Valley and the low grounds along other streams the water is usually found at depths varying from 5 to 12 feet. On the higher uplands its distance below the surface is greater, in some places even reaching 200 feet, and possibly more. The water is everywhere present except in a few small areas, such as the area in the northeast corner of the Dodge quadrangle, where the Benton limestone is exposed at the surface, and similar areas in the southeast part of the Meade quadrangle, where the Red Beds come close to the surface. Elsewhere, speaking in a general way, a well put down at random on any quarter section will produce water if carried to a sufficient depth.

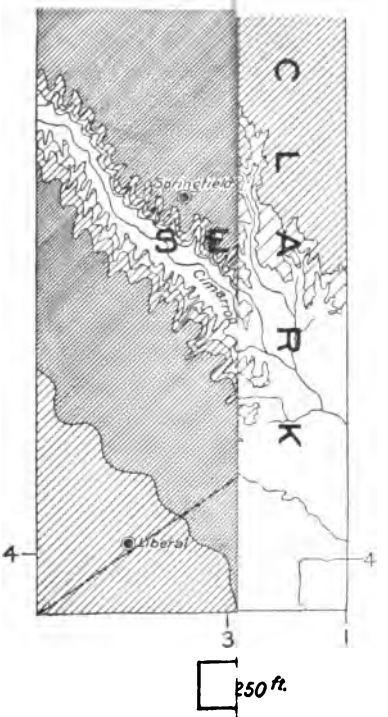
DEPTH OF TERTIARY GROUND WATER.

An attempt has been made to represent graphically the distance below the surface at which water may be found for the whole area. Extensive examinations were made during the past summer, which included an investigation of almost every well outside the Arkansas Valley. Mapping the location of the wells and noting the depth from which water had to be pumped, it was possible to draw a series of

lines on the surface of the map which may be called the water contours. These lines divide the area into a number of little groups, so that those similarly marked have water at about the same depth, somewhat as the contour lines on an ordinary topographic map represent areas of equal altitude. The results obtained by this method of representation are shown on the accompanying map (Pl. V), on which the different areas represented by the same pattern have the water lying at about the same depth from the surface. It may be said that too much confidence should not be placed in this map. When the long distances between wells on the uplands are considered, and the relatively large proportion of the uplands over which wells have not been drilled, it will be seen that it is necessarily impossible to construct a map of this kind which will be entirely accurate. Yet it is believed that the one here presented has a fair degree of accuracy, and that confidence may be placed in it to a moderate extent.

By an examination of the map it will be seen that along the principal river valleys the water may be found at a depth of 50 feet or less. Over the whole Arkansas Valley, aggregating 200 square miles or more, the depth varies from 5 to 12 feet. Likewise in the Meade artesian valley, along Crooked Creek, the surface water rarely exceeds 12 or 15 feet in depth. The valley of the Cimarron to the southwest is another place, where water can generally be obtained at a depth of less than 20 feet. An area to the north and northwest of Dodge, along the Sawlog and Buckner, covering many square miles, likewise has the water less than 50 feet in depth, while still another area in the southeast corner of Meade County, an area equal to 75 square miles or more, has water, when found at all, generally at a depth of less than 50 feet. This area, however, is one of the most uncertain ones in the county. The Red Beds are near the surface, with an irregular covering of sand and gravel. Sometimes the well will pass into the Red Beds without obtaining water in any considerable quantity, while perhaps less than a mile away water is found in apparently inexhaustible supplies. This variation of conditions seems to be due to the irregularity of the surface of the Red Beds, a condition which can not be foretold and which can be determined only by the extended use of spade or drill.

The areas over which water may be found at depths varying from 50 to 100 feet are greater in the aggregate than those just given. Nearly the whole of the country lying to the north of the Arkansas River comes under this division, although the high bluff lines along the Arkansas are not included. South of the river a strip reaches from west of Garden eastward entirely to the east side of the Dodge quadrangle. There is another area of like depth through the high divide between the Arkansas and Crooked Creek, covering the main portions of the south part of Ford and Gray counties and reaching far into Meade County on each side of the artesian valley and along Crooked



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Creek, with irregular areas in the east-central part of Meade County and lesser outlying areas elsewhere.

The next contour, with a depth varying from 100 to 150 feet, covers a like area and includes a portion of the high divide from Dodge westward almost to Garden, a portion of the divide between the Arkansas River and Crooked Creek, and a large portion of the high uplands in Meade County and a considerable part of Haskell and Finney counties. The area covered by the next contour interval, that of from 150 to 200 feet, covers nearly all the remaining territory. North of the Arkansas River it is represented by a small, irregular strip near Dodge. Southward it covers the remainder of the high divide between the Arkansas River and Crooked Creek and a small portion of Meade County to the southeast of Meade. It likewise occupies a large territory north of the Cimarron River, in the vicinity of West Plains and Springfield, reaching northward to beyond Santa Fe, thus occupying nearly all the broad, apparently level plain from Santa Fe to Springfield. The contour interval greater than 200 feet is represented in but few places in this area so far as we know. A few miles to the north of West Plains wells were found which were more than 200 feet deep, likewise in the southwestern part of Seward County and in an area northwest of Santa Fe. Could a larger number of wells be drilled over the high plains of Seward and Haskell counties, it is quite possible that this contour interval would be extended.

LEVEL OF TERTIARY GROUND WATER.

The water contours cross and recross the elevation contours in an irregular manner. In one respect they are independent of the elevation contours, and yet over small areas they bear a close relation to them. Thus on a given farm a well in the valley will have to be sunk a much less depth than on the uplands near by, and the difference in depth can usually be closely estimated by obtaining the difference in the surface elevation. For example, water in the Arkansas Valley at Cimarron can be had at a depth of from 6 to 12 feet, while 2 miles to the north, on the uplands, 140 feet higher, a well would probably have to be sunk 150 feet before water could be reached. We may cover much wider areas and still find the same condition obtaining in a general way. If a closer scrutiny of the conditions over wide areas be made, it is found that the upper surface of the available water is by no means on a level, but that it has marked variations of elevation which in a general way agree or correspond with the upper surface of the Cretaceous formations which lie buried beneath the Tertiary sands.

These conditions are well illustrated by the six different geologic sections crossing the area to be described. By reference to them (Pl. IV) it will be seen that the water level in the various wells is almost independent of the distance below the surface of the ground, but that

it is largely dependent upon the distance above the impervious floor. In directions along which the floor lies in a horizontal position the water level is likewise approximately horizontal. In directions along which the floor varies greatly in elevation the water level likewise varies. Thus in section 1, passing north and south along the one hundredth meridian through Dodge, the same as in sections 2 and 3 having a north-south direction, the water level is approximately horizontal wherever the Cretaceous floor is horizontal. Along the southern portion of section 1, where the upper surface of the Red Beds dips so rapidly to the south, the water level correspondingly falls at the same rate.

In the Cimarron Valley, in the vicinity of Englewood, the water is found at less than 2,000 feet above the sea level, while 25 miles to the north it is found at nearly the same depth below the surface, which makes it fully 2,400 feet above sea level, or 400 feet higher. We therefore have an average inclination of the water level southward along the one hundredth meridian, from Minneola toward Englewood, of more than 25 feet to the mile. In east and west directions we likewise find perceptible inclinations of the water level. Section 5, drawn east and west through Santa Fe, shows a fall of fully 200 feet in 56 miles, while section 6, passing east and west near Garden, shows a decline of the water surface of fully 300 feet in the same distance, or a fall of over 5 feet to the mile.

The same conditions are found to obtain over areas much wider even than that covered by this report. The water in the Arkansas River Valley at Coolidge is no farther from the surface than at Dodge, although the latter is about 860 feet lower, or at Great Bend or Hutchinson or Wichita or Arkansas City, although all the latter points are much lower than Coolidge. Similarly, the water of the high uplands anywhere in western Kansas, in general, is found at about the same depth, whether near the western side of the State or near the eastern limit of the Tertiary, although the difference in elevation may be a thousand feet or more. It is, therefore, correct, in a general way, to speak of the upper surface of the ground water as being approximately level when limited distances are considered, or when a distance extending in a direction which chances to cover a level surface of the underground Cretaceous floor is considered. The elevation contours are consequently of great value in determining the depth to which a well would have to be carried to obtain water if located near a well of known depth. But if the prospective well is to be drilled 5, 10, or 20 miles from any known well the elevation contours would be of but little if any value.

The existence of such vast quantities of water in an arid and semi-arid portion of the Great Plains appears very remarkable. Could the thousands of pioneers who traversed these regions prior to the operation of the transcontinental railway lines have known that the purest

and sweetest water existed in such unlimited quantities at so short a distance beneath the surface, how many of them in a few hours' time with spade and shovel would have supplied water to slake the thirst and maintain the life of man and beast throughout the course of those perilous journeys! But the idea of such quantities of water existing within easy reach rarely entered their minds. It took years of occupancy of the Great Plains by thousands of citizens for such an idea to become well established. Even now, after almost ten years of active agitation of the subject, few people outside the immediate localities where such water exists realize the extent to which water may be found.

As already explained, the whole country is underlain by a mass of impervious material, the Cretaceous formations, or the Red Beds. This impervious floor prevents the downward movement of water which may be above it. The Tertiary sands, gravels, and clays furnish a thin and moderately even covering on the top of this floor, a loose, porous covering, well adapted for absorbing all precipitation that may fall upon it and well suited for the transportation through it of water from one part of the country to another. It is not necessary, therefore, that the water under any particular area should have fallen as rain or snow immediately upon that area, but it may have been precipitated tens or hundreds of miles away and traveled by the slow movement now known to exist. Nor is it necessary to assume that all this water must have been precipitated within recent times. There is no reason for believing that climatic conditions on the Great Plains have sensibly varied for thousands of years. The rains throughout this long period have been falling as at present, and such portions of them as were not carried away by the run-off or by surface evaporation or held as soil moisture have sunk to the floor and there await the drill and the pump. As the water accumulates above the impervious floor it first moistens the sand to the degree of saturation, and any excess is held under such conditions that it can be drawn off by proper methods.

As the downward percolation continues, the level at which available water exists gradually rises, so that in the true sense of the term we may speak of the ground being saturated upward, meaning thereby that in the natural order of the events of accumulation the level at which the ground water first became sufficiently abundant to yield a supply was immediately above the impervious floor, and that, with the increase of water from above and from the sides, this level of available water gradually rose in a manner similar to the way the upper surface of water in a vessel rises when water is added. The upward saturation of the sands and gravels, therefore, is dependent upon the accumulation of a larger supply of water from precipitation or from underground movements.

We may think of this body of underground water as existing in

the form of a lake or pool; not a lake with a perfectly level surface, nor one filled entirely with water, but an underground lake the upper surface of which is inclined in any particular direction, dependent upon the relative conditions of supply and exhaustion and the rapidity with which water may move through the sands. Let us again refer to fig. 1, explained in the introduction, the figure representing the underground conditions at Lawrence, in the vicinity of the State University. Here we have a lake in one sense of the term, an area holding an excessive amount of water, so that the smallest opening made in it is instantly filled by the water flowing into it from all sides, just as an opening in a body of water will be filled by the movement of the adjacent water from all directions. But the upper surface of this lake is not level, because the water movement is so retarded that in the lower portions of the ground it can move neither upward nor laterally as rapidly as the supply is brought from above; consequently there is a piling up of the water similar to the way grain may be piled up in a bin.

This represents the conditions in the western part of Kansas, the only essential difference being that the Tertiary sands and gravels permit a more rapid movement than can be obtained in the clays at Lawrence. This great underground lake or sheet of water is consequently uneven of surface and variable in depth. A depression in the floor will be filled or partially filled, so that the water-bearing sands in the valley of the depression will be thicker than on the sides. And yet we may have a floor inclined 10 or 20 feet to the mile, with the water-bearing sands uniformly distributed over it, so that the water will lie at about an equal distance above the surface of the floor over the whole plane.

MEADE COUNTY WELLS.

The Meade artesian area is located in the valley of Crooked Creek, to the northeast of Meade Center, extending from Meade Center to Wilburn. This gives it a length of about 20 miles, with a width in places of nearly 6 miles. The area over which artesian water has been found to a greater or less extent covers from 60 to 80 square miles. It is a broad, flat valley, apparently almost level, with scarcely any irregularities of surface within it, except here and there small drainage channels which are cut downward from 5 to 8 feet, almost like an artificial ditch. On all sides and in every direction from the valley the ground is higher, so that there appears to be a natural wall all around it. On the east and southeast the wall is from 50 to 100 feet high, with gently sloping sides, and the surface is largely covered with sand hills. On the north is a gentle rise toward Crooked Creek, producing a maximum elevation of about 75 feet between the main part of the valley and Crooked Creek itself. But at the northeast, toward Wilburn, the wall is much more abrupt, rising rapidly to a height of 100 to 140 feet. A few drainage channels originate in the high ground to

the west and pass across the artesian valley to Crooked Creek. Such channels present the appearance of mere ditches throughout their whole length within the valley, usually having their banks lifted higher than the ground some distance back, showing the filling-in process to have been carried on by them, as is so commonly done by rivers after reaching their base-level. Crooked Creek is, throughout the valley, scarcely distinguishable from some of its tributaries just described. It is almost insignificant in appearance, generally but a few feet wide, and can rarely be observed in the landscape until one is within a hundred feet of it, so closely does it resemble an artificial ditch in its general characters. It has also lifted its banks higher than the adjacent land to so great an extent that in some instances the surface a quarter of a mile away is lower than the top of the bank immediately at the creek.

The uplands to the west of the artesian valley increase in height rapidly, so that the plains to the north and northwest of Jasper, as shown by the Meade topographic sheet, are more than 2,700 feet high not more than 10 miles away, while the general elevation of the artesian valley is between 2,400 and 2,500 feet. The Tertiary ground water of the high plains to the west is found at a depth of from 125 to 150 feet; consequently the level of the water 10 miles to the west of the artesian valley is from 100 to 120 feet above the surface of the valley itself.

The artesian valley throughout is covered with Tertiary or Pleistocene deposits. The thickness of these formations is not known; the different artesian wells vary from 50 to 250 feet in depth, and no one of them has yet passed through the formations. To the north, beyond Crooked Creek, the Benton is shown at the surface in a few places and has been reached in many of the wells. To the northeast, a few miles beyond Wilburn, the Dakota was found by different wells. South of the valley the Red Beds appear at the surface, as the Benton and Dakota gradually grow thinner at the south until they disappear. It is further believed that the strata were here faulted so that the Meade Valley was sunk to an unknown distance, at least 100 to 150 feet, and that it has since been filled in to a considerable extent, probably in Pleistocene time. The character of the materials, as shown in the borings from different wells here and there over the valley, can not be distinguished from the Tertiary materials adjacent on all sides. It is composed of silt, clay, sand, and fine gravel, quite irregularly mixed, so that there is no greater continuity of the bedding planes than may be found in the Tertiary deposits elsewhere.

The mortar beds produced by the cementing of the coarse sand seem to be almost wanting, but here and there the finer sand and clay are frequently partially cemented by calcium carbonate, producing a certain degree of hardening similar to that observed in the mortar beds elsewhere. In character the cement so frequently assumes

a concretionary aspect that it seems probable it was deposited in the sands and clays by infiltrating water after they were placed where they are now found. The artesian water is drawn from the Tertiary or from Pleistocene beds composed of materials in every respect similar to the Tertiary materials surrounding the valley upon all sides. It seems sharply distinguishable from the Dakota artesian water known to exist to the north and northwest.

The whole of the artesian valley is supplied with the ordinary underground water, which may be found at from 5 to 15 feet below the surface. Its abundance is not known, as no one cares to use it. It would seem that it is sharply distinguished from the deeper-lying artesian water, as it has no apparent artesian properties. But at the same time it must be admitted that we are in relative ignorance regarding the reasons why the two are not connected.

The artesian wells at present in successful operation number considerably more than 300, an exact enumeration of them not having yet been made. In depth the wells vary greatly, some of them being but little more than 50 feet deep, while others are as much as 250 feet. There is a strong similarity between the materials passed through by all the wells if considered in a general way, but a lack of similarity if considered in great detail. Each one passes through the surface soil, below which it encounters alternations of clay, sand, and soil. The sand is frequently partly cemented, so that the well drillers speak of it as rock, but the layers thus cemented are rarely more than 12 inches thick, and frequently not more than 6 inches. Two wells within 40 rods of each other found a great variation in the number and relative position of the beds of clay, sand, and rock, but all of them passed through the same materials. So far as could be learned, there is no particular stratum which must be reached before artesian water is obtained. A mass of bluish clay, the color showing that considerable unoxidized organic matter is contained within it, frequently rests on the top of a bed of uncemented sand, stained yellow with iron rust. Such sand always contains water, generally the artesian water, and indicates by the degree to which the iron oxide is produced that the artesian water is a surface water which has not yet been robbed of its supply of oxygen gathered from the atmosphere.

But few wells have been studied carefully while being drilled. In August, 1896, the writer had a well put down especially for making an examination. It was located on the land of Mr. W. F. Foster, near the center of section 6, township 31 south, range 27 west. The drill used was one rented from Mr. Cooper, a well driller living in the valley. In addition to the bit on the end, a pump was attached so that water was forced down through the drill pipe, causing a constant flow upward outside of the pipe, the current bringing up the cuttings of the drill. In this way it was impossible to tell within a few inches, or possibly a foot or two, of the depth at which a change of material was made unless there was a change in the degree of hardness of the

material, so that the one turning the drill could detect the difference. The well was carried to a depth of 167 feet and obtained a moderate flow of water from a loose, yellow sand.

Well of Mr. W. F. Foster, on section 6, township 31 south, range 27 west.

No. of stratum.	Thickness of stratum, feet.	Description of stratum.	Total depth to bottom of stratum, feet.
1	7	Soil and subsoil	7
2	13	Mortar beds, almost entirely free from sand or gravel, small concretionary mass of calcium carbonate intermingled with the clay	20
3	11	Light-colored clay, grading into gray and grayish-blue in color	31
4	5	Blue clay which grades into No. 5	36
5	4	Light-colored clay which grades into No. 6	40
6	10	Blue clay	50
7	2	Mortar beds similar to No. 2	52
8	14	Blue clay	66
9	19	At depth of 66 feet began striking thin layers of hard substance, which seemed to be layers of sand sufficiently cemented with calcium carbonate to produce considerable resistance to the drill. Three or four of these were passed during 19 feet. They were separated from each other by beds of blue clay	85
10	3	A fine white sand at the top, grading into bluish sand at the bottom, and which was sufficiently cemented with calcium carbonate to produce a relatively solid rock	88
11	3	Blue clay, at the bottom of which was a hard sandrock similar to those above	91
12	11	Clay, with sand intermingled	102
13	3	Light-colored sand	105
14	1	Soft clay, grading into No. 15	106
15	6	Alternating layers of clay and sand sufficiently cemented to be noticeable	112
16	18	At 113 feet struck unusually (for this well) hard sand rock less than 1 foot thick, below which there was a frequent alternation of clay and sand partially cemented, the layers being from 2 inches to 6 inches thick	130
17	20	At about 130 feet a fine sand with clay was struck, a light bluish-yellow in color, which was 20 feet thick	150
18	10	At 150 feet the color changed to more of a reddish-brown	160
19	7	At 160 feet the sand became coarser and the clay redder in color. The drill gradually sank of its own weight, occupying less than two minutes in sinking 3 feet, while the pump was kept running. At the bottom of this formation the clay seemed to disappear almost entirely, and the artesian flow came from the coarse, yellowish sand	167

It was learned from Mr. Foster and the parties who did the drilling that a well previously drilled, located not over 40 rods to the west, struck almost none of the harder material. The house well of Mr. Marrs, a quarter of a mile to the east, one of the best wells in the valley, likewise struck none of the harder materials. Each of these two wells was drilled in about four hours' time, which further shows the soft character of the materials passed through. It was reported that a few wells not more than 50 feet deep have produced considerable amounts of artesian water. From this they increase in depth to a maximum of 250 feet, the depth of a well drilled on Mr. Cooper's place, about 2½ miles to the southwest of the Foster well.

With but one exception, no well has yet been drilled in this valley large enough to admit more than a 3-inch pipe. The drills that

have been available for use have been owned locally, and have been handled by men who have had but little experience in well drilling outside the valley. Usually a gas pipe from 12 to 18 feet long is put down to shut off the first water, after which no piping is used. In a few instances wells have been piped almost their entire depth. The best now flowing gave but little water when first drilled. They had a mild flow bringing up sand, the flow increasing as more sand was brought out. In some cases two or three wagonloads of sand have thus been thrown out by the water, after which time the flow reached a maximum amount and the movement of sand almost ceased. Little experimenting has been done to determine whether or not an increase of water could be produced by properly piping the wells, or by pumping them vigorously until all the loose sand was removed. It is quite possible that flows could be greatly increased by these methods.

An artesian flow may be found almost anywhere over the valley. Yet there are many instances in which wells have been drilled that did not yield a sufficient quantity of water to be of value. It is difficult to decide, with the data at hand, why some of the wells are successes and some are failures. In a few places the surface elevation seems to be a little too high. A well in the bottom of a ravine will yield a pretty good flow, while in one drilled on the banks near by, the water will rise almost to the surface, but not high enough to flow. In other instances two or more wells may be close together with the surface elevation the same, some of which will be good flowing wells and others not. It seems probable that this difference is due to two or more causes. The great diversity in the character of the material passed through in drilling the different wells makes it certain that the clay beds are irregular in formation and distribution. One can well understand how the disposition of these beds may cause a variation in the results obtained. A mass of clay may carry the water so deep that the drill can not reach it. Or it is possible for a mass of sand to be entirely surrounded by an impervious clay, so that a drill penetrating the sand will receive no flow because there is no pressure on the water the sand contains. The heterogeneous character of the clay beds, therefore, may be one of the main causes for such differences in wells so close together. The experience with wells which are of little value for weeks, or even months, after which time they become strong flowing wells, shows that in some way they become choked with sand, permitting only a mild flow until the sand is removed by pumping or otherwise.

It seems that the northern and western sides of the valley are the more productive. At present the best wells are in the northwestern portion of the valley, but flowing wells have been obtained all the way from Wilburn, on the northeast, to Meade, or possibly a mile or two south of Meade, to the southwest. The flow of the wells varies from a pailful in five minutes to 45 gallons per minute. Approxi-

VIEW OF VICK'S ARTESIAN WELL AND RESERVOIR, NORTH OF MEADE, KANSAS.

mate measurements have been made of twenty or more of the strongest wells. A large bucket was accurately measured and filled by the flow a number of times, one person handling the bucket, the other holding a watch to determine the number of seconds required for filling the bucket. The test was repeated a number of times to eliminate errors of observation as far as possible. In this way it is believed the probable error of measurement is not greater than 1 or 2 per cent. Five or six different wells were found to yield 45 gallons per minute. Twenty or thirty exist which yield 30 gallons per minute or more, from which the wells grade downward to the minimum flow.

The water obtained from the wells is largely used for irrigation purposes. Many of the wells were simply left flowing, and the water allowed to waste, without any attempt to use it. The number of acres irrigated is far less than the estimated possibility.

From data already given regarding elevations in the artesian valley and the uplands to the west, it will be seen that the water level from 5 to 15 miles to the west of the valley is considerably higher than the surface of the ground within the valley. The wells along the arroyos to the west of the artesian valley have artesian properties which gradually decrease westward. The depth of the water on the uplands to the west is nearly as great a mile away as it is 5 miles away, excepting where the well is located in an arroyo of considerable depth. It will not do, therefore, to consider the water on the uplands as moving eastward under favorable conditions for creating a pressure throughout the whole distance, but rather it should be considered that the impervious Cretaceous or Red Bed floor slopes to the east at nearly the same rate as the surface, and that the water is gradually moving down this gentle incline toward the east. Here and there, however, it passes under local clay beds, which carry the water to lower levels than it otherwise would occupy, and a corresponding pressure is set up. In some way, as the large artesian area is approached, the water descends, and in the descent passes underneath the clay beds of the valley, so that a limited pressure is established.

A few experiments were made to test the height to which water would rise in an open tube at the well. All such experiments show that the rise is only a few feet, perhaps always less than 20. The pressure which causes the flow from the wells, therefore, can not be due to the extra height the water has 10 miles to the west, otherwise the head would be much greater and the flow correspondingly stronger. It would seem rather that the pressure is due to the head generated by the gentle dipping downward of the water level as it passes under the clay beds near the west border of the artesian area, perhaps rarely extending farther away than from 2 to 4 miles. The water in the artesian wells seems to be continuous with the general upland water to the west. It is like it in character, and the two areas are connected by various wells.

Springs throughout the artesian valley are by no means unknown.

A few are located in arroyos along the western border. The most noted area for springs is in the vicinity of Mr. Simms's ranch, a mile and a half north of Fowler. On the eastern side of Crooked Creek, a fourth of a mile or more away, a large area is so abundantly supplied with springs and seeps that hundreds of acres of land are rendered worthless. The springs are principally located just along the border line between the valley proper and the higher lands to the east. The rank growth of vegetation produced by the moisture has provided a tough and heavy sod which protects the softer ground beneath, so that the range animals can pass over it with safety, except in the immediate vicinity of the strongest pools. Here the upward movement of the water is so rapid and the sand which is frequently brought up with the water accumulates to such an extent that vegetation does not grow for a few feet around the springs. Such areas are death traps to range animals. Mr. Simms stated that numerous instances have come under his observation of animals becoming ingulfed in the mud and sinking out of sight, or, if not out of sight entirely, sinking the full length of the body. In many of the springs, by using a long pole, one can feel bones at a distance of from 8 to 15 feet below the surface, presumably those of buffalo and other wild animals which lost their life in the springs. It seems probable that these springs and the artesian wells receive their supplies from the same source. The character of the water is the same; the location in general is the same; for artesian wells can be obtained in the immediate vicinity of the springs, and the whole character of the surroundings implies that there is no essential difference between the sources of the two classes of water. The location of the largest springs is near the southeast valley line, along the eastern side of the valley. If the valley has been dropped by faulting, the water-bearing sands in the valley are doubtless on a level with the Red Beds, or the underlying Dakota on the east. This condition would cause springs to be more abundant along the east line than elsewhere.

Farther south, along the western tributaries to Crooked Creek and in the valley of Crooked Creek itself, springs and seeps abound. The largest amount of spring water flows through Spring Creek, a stream about 3 miles south of Meade. Springs are abundant throughout almost the entire length of this stream, but are particularly so about 3 miles south of Meade, in section 21. Here most beautiful springs exist. At one place with an area of not more than 10 square rods, the cold, clear water comes bursting forth from under the mortar-beds bluff, forming a stream like a mill race. An approximate measurement from this one area gave fully 3 second-feet, which is equivalent to more than 2,000 acre-feet, or enough to irrigate more than 2,000 acres with 12 inches of water each year. This is one of the most remarkable groups of springs anywhere in the West. It would seem that there is an abundance of water, however, in this one little stream to irrigate more than 3,000 acres 12 inches each year, provided

HEAD OF IRRIGATION DITCH SUPPLYING THE "CROOKED L" RANCH, MEADE COUNTY, KANSAS.

Ditch to left; Spring Creek to right.

it were all used for irrigation purposes and proper care taken to guard against waste. About a mile below this group of springs a ditch draws water from Spring Creek to irrigate the alfalfa fields on Crooked L ranch. The remainder of the water passes on down the creek, and is principally used for stock water, although here and there small amounts are taken for irrigation. South from Spring Creek the next most important tributary from the west is Stump Arroyo, a stream along which frequent springs occur, but which does not yield nearly so much water. One principal ditch draws water from this creek to farms below. All these springs are in the true sense connected with the artesian area to the north, and the discussion of them is relevant here, because they throw light on the origin of the water in the artesian valley.

Reviewing the whole matter regarding the origin of the water in the artesian wells and artesian springs, it must be admitted that it seems the water is continuous with the ordinary underground water to the west, and that it is therefore a part of the same. It is certainly distinct from the Dakota water, and is so deep that we can not think it lies above the eastern extension of the water plane on the west.

It is of great practical importance to arrive at some conclusion regarding the amount of available water in the artesian valley, and to decide whether or not the continued use year after year is liable to destroy the supply. It will hardly do to assume that wells could be put down every few rods over the entire valley, each one of which would flow independently of the others. Artesian water in almost all places thus far observed in any part of the world has been found in wells which acted sympathetically with one another. When a strong-flowing well is closed, ordinarily adjacent wells have their flow accelerated. Few experiments have been thus far made in the Meade artesian valley to determine the influence of one well upon another. Many inquiries were made of citizens here and there in the valley, and conflicting statements were given on these subjects. Some individuals were positive that the rapid flow of one well sensibly diminished the flow in weaker ones near by, while other farmers as emphatically stated that on their farm the flow of one had no influence on the flow of another. It is probable that the former class of reports are correct; in fact, it would be quite remarkable were they not.

This condition need not necessarily argue against the large supply of water in the valley. In all cases where wells are close together they mutually influence one another, provided the rate of flow through the water-bearing strata—sand, gravel, or whatever it may be—is not sufficiently great to maintain the flow as long as the supply lasts. But most beds of sand and gravel are so close grained that there is an appreciable check in the rate of movement of the water in the sand, which in most instances will result in the sympathetic action of adjacent wells.

It appears to the writer, therefore, that the question of supply of water for artesian wells depends more on the source of the water than it does on the mere rapidity of the flow from any well or from a group of wells. The facts already given certainly imply, as has been seen, that the source is the ordinary ground water to the west and northwest. If this is correct, the question of supply is essentially the same as the question of the supply in the upland areas. So long as water exists on the uplands from 5 to 20 or 40 miles away, it is probable that it will likewise exist in the artesian wells. Could a sufficient number of wells be drilled, and could the flow be continued from all of them a sufficient length of time, it seems reasonable to suppose that a diminution of the supply of water on the uplands would first be observed, and later of that in the valley. It is probable that the small area, less than 100 square miles, in the artesian valley and the valley of Crooked Creek below Meade, could drain the whole of the uplands to the west, and that their supply of water would not become exhausted so long as there was any available water anywhere in the broad plains to the west or northwest. We are therefore brought to the consideration of the amount of this ground water, a subject discussed later in this report. It is sufficient to say here that, in the judgment of the writer, water enough could be obtained, were it properly husbanded, to irrigate such parts of the Meade artesian valley as anyone is likely to want to irrigate during the next half century.

QUANTITY OF TERTIARY GROUND WATER.

DIFFICULTY OF ESTIMATION.

No one can give more than a mere approximation of the amount of Tertiary ground water in western Kansas. The wells which thus far have been drawing their supply from it, with but few exceptions, have shown no indications of failing. A few wells which were located on the outer margin of the water area have been known to become exhausted by rapid pumping. Others which have only penetrated the water-producing sands a few inches, or a foot at most, have likewise been known to fail. But no instances have yet been found of a well failing, or seeming to be in failing condition, provided it was unquestionably within the water-producing area and had a depth of 5 feet or more in the water-bearing sand. Of course this does not necessarily mean that the supply is inexhaustible, in the true sense of the term. But it may well be taken to mean that with any moderate amount of pumping—even an amount several times greater than has yet been pumped—the supply will not be found wanting.

It is supposed, and perhaps correctly, that water is more abundant in the Arkansas River Valley than on the uplands either north or south. More decisive pumping tests have been made here than at any place on the uplands. The city well at Garden represents the severest

WINDMILL AND RESERVOIR AT GARDEN, KANSAS.

test made within this area, a supply sufficient for a town of 2,000 inhabitants being furnished. The largest pumping plant within the State is located in the Arkansas Valley, at Hutchinson. Here the Hutchinson Packing Company have three pumps which have been running constantly for several months, pumping at the rate of about 1,300 gallons per minute, the equivalent of 5,616,000 gallons per day, without appreciably affecting the water supply. This is almost 3 second-feet, an amount approaching the flow from the big springs already described along Spring Creek. There is no reason for believing that the amount of water here is any greater than anywhere else in the valley from Coolidge to Arkansas City. A like amount, probably, could be pumped from every quarter section of land within the whole valley. Should such pumping be done all at once, it doubtless would decrease the supply, but no fear need be entertained that the water will not be sufficient for all demands that will be made upon it for a long time in the future.

Could the water level in the valley be appreciably lowered, it is quite evident that water would be drawn into the valley from the upland areas to the south, and to some extent from those to the north. The rapidity with which the movement toward the river would be made would depend upon a number of conditions, such as the degree of exhaustion and the character of the material through which the movement takes place. Should the draft be sufficient to lower the water in the valley 20 feet, there would result a high angle of inclination on the upper surface of the water at either side, tending to set up a rapid movement from both sides into the valley. Still, a gradient of 20 feet to the mile is less than now exists under normal conditions in the area to the north and west of Englewood, and yet the water is not drawn away so rapidly but that it is almost everywhere present. Should any other area be appreciably exhausted by the excessive pumping from a well, or a group of wells, so that the upper surface of the water would be materially lowered, water would flow in from all directions to supply the deficiency, and in this way the one well would drain a considerable area.

Is is therefore exceedingly difficult to draw decisive conclusions regarding the sum total of the water in the Great Plains of the West, judging from the amount that any given well or series of wells may produce, so long as the pump does not entirely exhaust the area. All that can be said with certainty at the present time is that, with the large amount of pumping which has already been done, no indications of exhaustion have yet been observed.

SOURCES OF TERTIARY GROUND WATER.

It is of great importance to consider the sources of the supply and the rapidity with which the supply can be transmitted to different localities. Should we look upon the ground water as constituting a great reservoir, it is evident that the amount would become entirely

exhausted unless there were a corresponding continuance of the supply. Should pumping be begun from Lake Michigan, it would sooner or later entirely exhaust that vast body of water were it not for the large additions to its volume every year by the surface drainage of adjacent territory. It is possible to determine the amount of pumping that could be done without appreciably lowering the water in the lake, by an estimation of the amount of water added by the surface drainage year by year. Likewise the question of the supply of water for western Kansas is largely one of the rate of the renewal of the ground water. Any estimation on the subject which neglects this factor will in practice prove to be faulty, should the time ever come when the sum total of exhaustion is more rapid than the rate of supply. Enough is known on the subject to demonstrate that pumping from the underground reservoir must be many times greater than that which has yet been done before the exhaustion will nearly equal the rate of supply. In many places throughout the country springs of great strength abound, and lesser seeps supply water to pools and living streams. Should the exhaustion by pumping be appreciable, it would first be noticed in the rate of flow of the springs and seeps. Nothing of the kind has yet been observed.

The original source of all the Tertiary waters is precipitation. The areas over which this precipitation falls are large and varied. In Meade County the average rainfall is about 18 inches per annum, a rainfall which varies from year to year and from month to month. Sometimes heavy falls are known, reaching from 3 to 4 inches or more at a single storm. With such storms an undue proportion of the water runs off through the drainage channels, leaving perhaps less than half to be absorbed by the ground. At other times the rain is so light that it will wet the ground for only a few inches, and entirely evaporate within a few days or weeks, so that perhaps no appreciable part of the lighter rain joins the general ground water.

The character of the soil has a great influence on the run-off. In the sand hill area to the south of Arkansas River and to the east of Crooked Creek, and in the southeastern corner of Meade County, it requires an unusually heavy rain for any of the water to join the run-off, the whole of it being absorbed and held by the porous sands. On the uplands, where the Plains marl is abundant, as well as in the river valleys, where a similar soil exists, the character of the soil is such that only a small amount of the rainfall is absorbed, while a correspondingly large proportion joins the run-off. The conditions of the rainfall and the character of the surface soil over the whole of the Tertiary of western Kansas and eastern Colorado are about the same on the average as in the area covered by this report. Probably more than half of the total precipitation falls in severe storms, or in light rains. We have, therefore, unfavorable conditions for the absorption by the ground of a high per cent of rainfall. No one has

made any accurate observations on this subject with a view to determining the per cent of the total rainfall which is absorbed by the ground; but, as seen in the Introduction, it is only a small part of the total amount absorbed that ever becomes available as water supply.

The Tertiary formations extend west, in some places reaching almost to the Rocky Mountains, but in other places they are separated from the foothills by the high ridge known as the "Hogback," and by the high divide farther north. Toward the mountainous area generally the rainfall increases, so that the average annual precipitation is greater than in the west of Kansas.

A great deal has been said and written regarding the probability that precipitation in the mountainous region will reach western Kansas. It may be added that little, if anything, is positively known on the subject. We have the Arkansas River carrying its waters all the way from the mountains through the Great Plains. The eastward inclination of the surface is such that the water in the bed of the stream at one place is higher than the uplands only a few miles below. Here and there throughout its course the Benton or Dakota bluffs hem the water in, so that it is confined to the channel of the stream. At other places such impervious bluffs do not exist, and the loose, porous Tertiary sands and gravel spread from the uplands directly down into the river valley. There are many places where, so far as the elevation of the underground floor itself is concerned, underground water may be drawn from the Arkansas River and spread over all the vast plains lying below. Whether this actually occurs or not can be determined only by a careful and detailed study of the water levels north and south of the river. At present we have so few wells in the great sand-hill area south of the river in Kansas and Colorado that no conclusion of value can be reached in this discussion. The level lines have shown that the water in the wells 6 or 8 miles south of the river at Garden is at a little lower level than the water in the river itself. The same in a general way is true at Dodge.[1] Later investigations have added but little information on this subject for the areas covered by the sand hills, the difficulty being that so few wells here exist.

From the meager data at hand, we are forced to conclude that at different places throughout its course, so far as the water gradients are concerned, ground water might be deflected from the river valley southward in its eastward movement and ultimately become a part of the great body of ground water on the plains only a few miles farther east. If such deflection ever occurs, we have a mass of water gathered from the rains and melting snows in the mountainous area being carried across the divide by the Arkansas River and ultimately spreading over the high uplands to the south of the river. This is only one of the conditions which are possible, so far as the information now at

[1] Report on Irrigation, 1893. Artesian and Underflow Investigation. Fifty-second Congress, first session, Senate Ex. Doc. 41, part 2, pp. 26-27, pls. 10 and 11.

hand indicates. It is entirely improbable, however, that any considerable proportion of the water in the plains south of the river comes from the river itself. It is probable that if a detailed examination were made it would be found that the water in the sand-hill region is a little higher than in the river. This statement is made because it is customary for rivers to serve as drainage channels rather than as supply channels. The usual condition is for underground drainage to be from the uplands into the rivers, the same as the surface drainage.

Should a considerable proportion of the water be deflected from the Arkansas River Valley to the plains at the south, we should find a much larger amount of water south of the river than exists to the north, unless there is a similar deflection in places to the north. There are some reasons for thinking that this may be true. Farther east, in Clark, Comanche, Kiowa, Pratt, and Stafford counties, and the level lands to the east toward Wichita, there is a larger proportion of springs and streams with living water in them than we find in general to the north of the Arkansas. But it must be confessed that with so few absolute data as are now available regarding the actual amount of ground water, arguments pro and con on this question are of little worth. A careful study of the subject would be of value.

At different places along the Arkansas, where the bluff lines of the valley are composed of Tertiary material, both in Colorado and Kansas, soundings should be made at frequent intervals to determine accurately the level of the ground-water surface both north and south of the river. If it should be found that there is a uniform rise of the level outward from the river, this would show that the underground drainage is uniformly toward the river rather than away from it. If, on the contrary, at any time during the year in periods of high water it should be found that the ground water at or near the river is higher than at localities farther back to the south or north, this would seem to show the possibility, and even the probability, of water being deflected from the river toward the general uplands. The direction of the movement need not be at right angles with the river, nor nearly so, but probably would be in directions somewhat similar to those usually followed by drainage channels which draw water from the river. If such lateral deflections of ground water are made to appear probable, there can be no doubt that at least a portion of the precipitation over the mountainous areas drained by the Arkansas and the Platte rivers may become spread out over the great upland plains and furnish an essential part of the plains ground water. If, on the other hand, such deflections of ground water in the river valleys are shown to be impossible, it may well be doubted if any of the mountainous precipitation joins the ground water of the plains.

It must be remembered that the underground movement is governed largely by the character of the surface of the underground

ST. JACOB'S WELL, CLARK COUNTY, KANSAS.

Cretaceous floor which has already been described. There are strong geologic reasons for believing that this Cretaceous floor in most places east of the foothills has a greater elevation than the underground water level in the great trough-like area trending north and south to the west of the "Hogback" and the high divide, so that the eastward motion of the water would be impossible, except here and there where there might be a channel or depression in the Cretaceous floor similar to those along the Arkansas and Platte rivers.

Whatever conclusion may ultimately be reached regarding the possibility of an eastward underground movement from the mountains themselves, the rate of the movement of the water through the sand is, after all, of the most importance. When water is being pumped from a well, it is not so important to know the amount of water 10, 50, or 100 miles away, as it is to know the rate of movement through the sand of the water immediately adjacent the well. The maximum supply that the well can furnish will be dependent upon the rate of the inflow to the well, and only remotely upon the sum total of the water over the whole area. The rate of movement is likewise of great importance in considering the total amount of available water on the plains as a whole.

Should the precipitation and the proportion of the precipitation which joins the ground water be greatly increased, unless the possible rate of underground movement were correspondingly increased, available masses of water would tend to pile up where the precipitation occurs, without sensibly affecting the supply in other parts of the country. Those who believe in a mountainous source for a part or the whole of the plains water must therefore be able to show that the rate of eastward movement is sufficiently rapid sensibly to increase the available water at different places on the plains. Otherwise the increased precipitation in the mountainous areas would be of no avail.

It is doubtful if laboratory tests are of much value in this discussion, because the conditions governing them are not applicable. The inclination of the surface, the porosity of the strata, the ease with which water may pass from one stratum into another as the strata become discontinued, are some of the questions which must be considered. In any experiment neglect of any one of these conditions, and probably others not yet fully understood, will cause the results obtained to be of little if any value in this consideration. We may have a mass of sand or gravel largely composed of coarse grains or pebbles, so that at first thought it would seem that water would flow freely through it. If, however, there is a small amount of silt or clay disseminated through the mass, this will have a most important influence. The coarse masses of gravel in such cases not only do no good, but do harm; for each grain, being impervious, renders just that much space

impervious. It is probable that the rate of flow through a heterogeneous bed of this character is governed by the finest materials in the bed. Investigations of the subject, therefore, must consider the detailed geologic conditions of the area studied.

SUMMARY.

In summarizing the foregoing discussions regarding the amount of water, it may be concluded that there is a surprisingly large amount of water in the Arkansas Valley, and a similarly surprisingly large amount on the uplands, although perhaps smaller than in the valley. The springs along Spring Creek are the best single evidence we have of the large amount on the uplands, and the pumping tests in the valley, particularly at Hutchinson, are the best tests we have of the amount in the valley. These, combined with the almost universal presence of water, and the meteorologic and geologic conditions already explained, furnish good reasons for believing that the amount of ground water under the area here described is sufficient to meet any demands that will likely be made upon it, even should industries spring up in the West which will use many times as much water as now seems probable. The greatest needs for western Kansas now, and for the whole plains area, are better methods of raising water from beneath the surface, and better methods in using it.

IRRIGATION DEVELOPMENT.

Irrigation is now practiced to a considerable extent in the Arkansas Valley and along the Cimarron River and Crooked Creek. Numerous small reservoirs and irrigation pumps are also established on the uplands, some of which have proved to be surprisingly successful. In the valleys the principal crops raised by irrigation are alfalfa and fruit, but on the uplands little is irrigated besides gardens and fruit.

The water in the Arkansas River is so low during the greater part of the year that the canals are dry, but in times of freshets they are used to a considerable extent, and the thousands of acres of alfalfa and orchards and other crops are quite thoroughly irrigated once a year at least, and upon the average two or three times. This is sufficient to produce a moderate crop of alfalfa during a dry year, while in an ordinary season it will give from three to four cuttings of hay.

The acreage varies from year to year, depending upon many matters which affect the prosperity of the farmers in that part of the State.

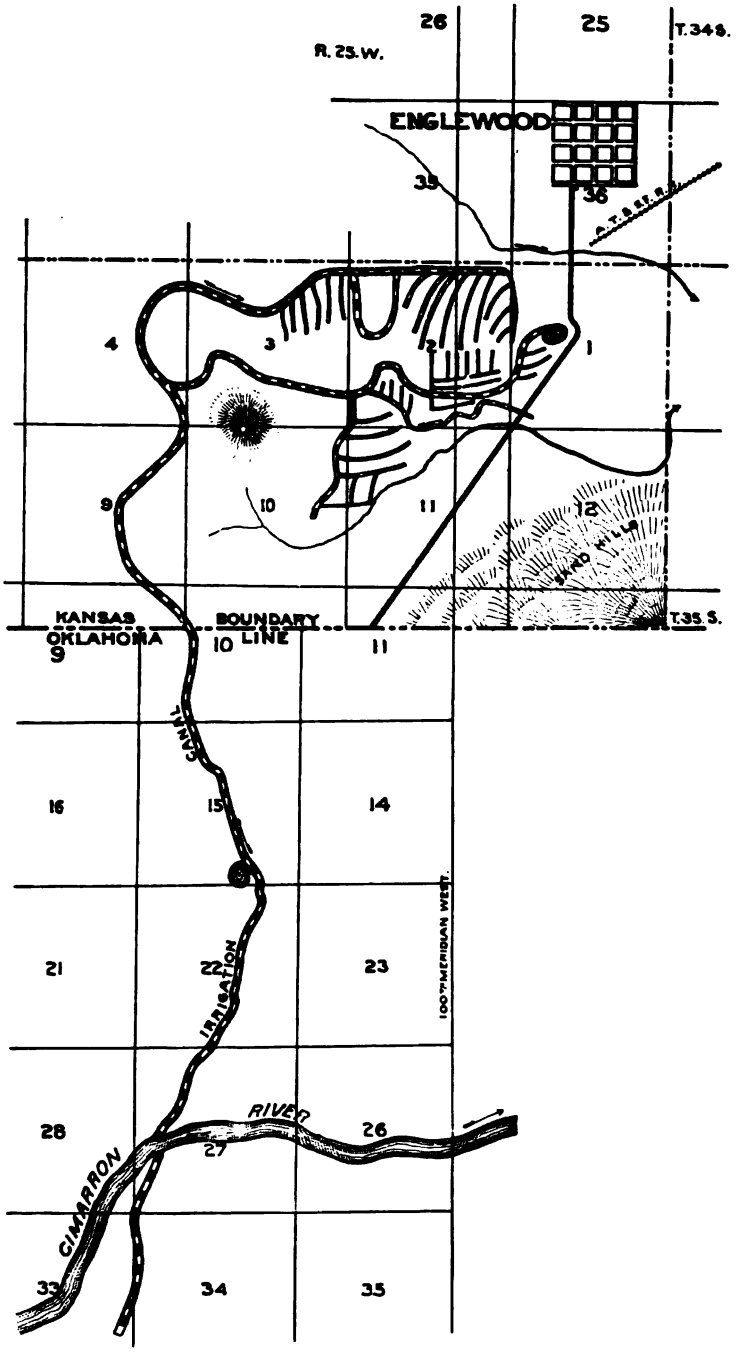
Several hundred acres are also irrigated in the valley from pumps. In most places the water is raised less than 12 feet, so that windmills are very efficient, a 14-foot wheel furnishing ample power to run an 8-inch pump that will throw from 5 to 8 gallons at a stroke. Irrigation from mills is on the increase, as it frequently happens that dry weather in the spring and early summer is disastrous before water from the river is available.

HEAD OF PERRY IRRIGATION CANAL, CIMARRON RIVER, NEAR ENGLEWOOD, KANSAS.

Cimarron River carries a large amount of water during a part of the year and is rarely dry in this part of the State, as it is fed by springs from the ground water. Irrigation is practiced to a considerable extent in different places along the valley. The largest tract under water from the river at present is the Clearmont ranch of Col. C. D. Perry, at Englewood. This ranch at present has about 1,100 acres under ditch, but Colonel Perry's plans are to reduce this amount to 800 acres, as he thinks the same amount of labor expended on a smaller acreage will give better returns than when spread over a larger piece of land. Formerly general farming was conducted at this ranch, but it has been found that with the markets as they have recently been it is more profitable to raise feed for stock and to market the animals. During the summer of 1896, therefore, no field crops of consequence were raised except alfalfa, sorghum, and kaffir corn, each of which grows with great luxuriance. Pl. XII is a map of Clearmont ranch, showing how the water is drawn from the Cimarron and the principal laterals employed in distributing it over the ranch.

At certain times in the year the water in the Cimarron is slightly salty, particularly in dry weather. This apparently produces no bad soil effects, principally because the most irrigation is done at times when the river is flush and consequently the water least salty.

The large amount of water furnished by the springs of Spring Creek is partially used on the Crooked L ranch, which lies in the valley at the junction of Spring Creek and Crooked Creek. Here about 500 acres are under irrigation, devoted principally to alfalfa, the water for which is drawn from Spring Creek. Pl. VIII is reproduced from a photograph, showing the head of the supply ditch. Below the mouth of Spring Creek a few small fields are irrigated from the creek, but none so large as the Crooked L ranch.



MAP OF CLEARMONT RANCH, NEAR ENGLEWOOD, KANSAS, SHOWING HOW WATER IS DRAWN FROM THE CIMARRON AND THE PRINCIPAL LATERALS.

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DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 7

SEEPAGE WATER OF NORTHERN UTAH.—FORTIER

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

The following list contains the titles and brief descriptions of the principal reports relating to water supply and irrigation prepared by the United States Geological Survey since 1890:

1890.

First Annual Report of the United States Irrigation Survey, 1890, octavo, 123 pp.

Printed as Part II, Irrigation, of the Tenth Annual Report of the United States Geological Survey, 1888-89. Contains a statement of the origin of the Irrigation Survey, a preliminary report on the organization and prosecution of the survey of the arid lands for purposes of irrigation, and report of work done during 1890.

1891.

Second Annual Report of the United States Irrigation Survey, 1891, octavo, 395 pp.

Published as Part II, Irrigation, of the Eleventh Annual Report of the United States Geological Survey, 1889-90. Contains a description of the hydrography of the arid region and of the engineering operations carried on by the Irrigation Survey during 1890; also the statement of the Director of the Survey to the House Committee on Irrigation, and other papers, including a bibliography of irrigation literature. Illustrated by 29 plates and 4 figures.

Third Annual Report of the United States Irrigation Survey, 1891, octavo, 576 pp.

Printed as Part II of the Twelfth Annual Report of the United States Geological Survey, 1890-91. Contains a report upon the location and survey of reservoir sites during the fiscal year ending June 30, 1891, by A. H. Thompson; "Hydrography of the arid regions," by F. H. Newell; "Irrigation in India," by Herbert M. Wilson. Illustrated by 93 plates and 190 figures.

Bulletins of the Eleventh Census of the United States upon irrigation, prepared by F. H. Newell, quarto.

No. 35, Irrigation in Arizona; No. 60, Irrigation in New Mexico; No. 85, Irrigation in Utah; No. 107, Irrigation in Wyoming; No. 153, Irrigation in Montana: No. 157, Irrigation in Idaho; No. 163, Irrigation in Nevada; No. 178, Irrigation in Oregon; No. 193, Artesian wells for irrigation; No. 198, Irrigation in Washington.

1892.

Irrigation of western United States, by F. H. Newell; extra census bulletin No. 23, September 9, 1892, quarto, 22 pp.

Contains tabulations showing the total number, average size, etc., of irrigated holdings, the total area and average size of irrigated farms in the subhumid regions, the percentage of number of farms irrigated, character of crops, value of irrigated lands, the average cost of irrigation, the investment and profits, together with a résumé of the water supply and a description of irrigation by artesian wells. Illustrated by colored maps showing the location and relative extent of the irrigated areas.

1893.

Thirteenth Annual Report of the United States Geological Survey, 1891-92, Part III, Irrigation, 1893, octavo, 486 pp.

Consists of three papers: "Water supply for irrigation," by F. H. Newell; "American engineering and engineering results of the Irrigation Survey," by Herbert M. Wilson; "Construction of topographic maps and selection and survey of reservoir sites," by A. H Thompson. Illustrated by 77 plates and 119 figures.

A geological reconnoissance in central Washington, by Israel Cook Russell, 1893, octavo, 108 pp., 15 plates. Bulletin No. 108 of the United States Geological Survey; price, 15 cents.

Contains a description of the examination of the geologic structure in and adjacent to the drainage basin of Yakima River and the great plains of the Columbia to the east of this area, with special reference to the occurrence of artesian waters.

1894.

Report on agriculture by irrigation in the western part of the United States at the Eleventh Census, 1890, by F. H. Newell, 1894, quarto, 283 pp.

Consists of a general description of the condition of irrigation in the United States, the area irrigated, cost of works, their value and profits; also describes the water supply, the value of water, of artesian wells, reservoirs, and other details; then takes up each State and Territory in order, giving a general description of the condition of agriculture by irrigation, and discusses the physical condition and local peculiarities in each county.

Fourteenth Annual Report of the United States Geological Survey, 1892-93, in two parts, Part II, Accompanying papers, 1894, octavo, 597 pp.

Contains papers on "Potable waters of the eastern United States," by W J McGee; "Natural mineral waters of the United States," by A. C. Peale; "Results of stream measurements," by F. H. Newell. Illustrated by maps and diagrams.

(Continued on third page of cover.)

DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 7

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

UNITED STATES GEOLOGICAL SURVEY
CHARLES D. WALCOTT, DIRECTOR

SEEPAGE WATER OF NORTHERN UTAH

BY

SAMUEL FORTIER

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

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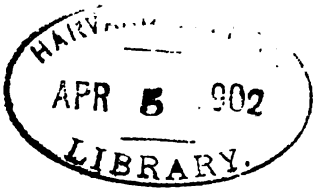

Chas Moore

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, April 13, 1897.

SIR: I have the honor to transmit herewith a paper entitled Seepage Waters of Northern Utah, by Samuel Fortier, professor of irrigation engineering at the Agricultural College at Logan, Utah. The facts herein presented are based upon field work carried on mainly during the summer of 1896, and have special value in illustrating conditions which prevail to a greater or less degree throughout all irrigated lands, especially within inclosed valleys or on long, narrow drainage systems.

One of the matters which most complicate and embarrass the adjudication of water rights and the strict enforcement of priorities of appropriation arises from the fact that a considerable volume of water available for irrigation during the critical season of the year, when the crops are maturing, comes from the seepage from lands higher upstream to which water has been applied earlier in the year. In some cases these lands have been irrigated in defiance of a strict construction of the law regarding the priority of right to use water, but it has been claimed that such use, instead of being a detriment to the lands below, has been a benefit, and, in fact, that there has been more water available in consequence of this use than could otherwise be had. The determination of these matters requires careful measurement and study in each case, but the work of Professor Fortier serves to indicate what may be expected under similar conditions and illustrates methods applicable to this examination.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

SEEPAGE WATER OF NORTHERN UTAH.

By Samuel Fortier.

LOCATION AND PURPOSE OF THE INVESTIGATION.

The term "seepage water" is used by the irrigators of the West to designate the water which reaches the lowest grounds or the stream channels, swelling the latter by imperceptible degrees and keeping up the flow long after the rains have ceased and the snow has melted. The word "seepage" is applied particularly to the water which begins to appear in spots below irrigation canals and cultivated fields, usually some months or even years after irrigation has been introduced, and which tends to convert the lowlands into marshes and gives rise to springs, which in turn may be employed in watering other fields.

The importance of a thorough knowledge of the behavior of seepage water is obvious when consideration is given to the close relationship which exists between the available water supply and the material prosperity of the arid region where irrigation is practiced. This is particularly true of Utah, where every readily available source of supply has long since been utilized and where the rapidly increasing agricultural population necessitates the complete utilization of all fresh waters.

The measurements and investigations of seepage water described in this paper have been confined mainly to Cache Valley, being included within three counties in northern Utah, Weber, Boxelder, and Cache, and one county, Oneida, in Idaho. The conditions may be taken as fairly typical of those in the entire State, and to a less extent of those of adjacent States. A full knowledge of the seepage water will be of inestimable value in the development of Cache Valley, owing to the conditions now existing. The towns and farming communities were settled for the most part from 30 to 40 years ago. The tributaries of Bear River have supplied all irrigating waters, and many of the ditches and canals have water rights extending over a period of 30 years. These early ditches were the first built to divert water from Bear River and its tributaries, and according to the law of prior appropriation which prevails in Utah, Wyoming, and Idaho, the three States through which Bear River flows, the early canals of Cache Valley have water rights prior to all others. Boxelder County has

at least a quarter of a million acres of fertile irrigable land, and with the exception of Boxelder Creek, Willard Creek, and other small streams whose aggregate summer flow does not exceed 40 second-feet, it is entirely dependent upon Bear River for the water necessary to irrigate its extensive area.

The time is not far distant when conflicts over water rights must arise between the irrigators of these counties, and it is therefore highly important to collect and record now all the physical data possible pertaining to the capacities of the irrigating ditches, the areas watered by each, and the general behavior of all sources of supply. To put off the collection of such facts until litigation has begun, and to attempt to render court decisions upon the conflicting testimony of interested witnesses only, is full of danger. Moreover, a study of the hydrography of Bear River and its tributaries is complicated, owing to the fact that three States obtain water from this one source. During the next drought many of the irrigators of northern Utah are liable to suffer serious loss from a scarcity of water in Bear River, caused by its diversion through canals in Wyoming and Idaho. If the law of prior appropriation is to be accepted for interstate priorities, it is of the utmost importance that all existing water rights be clearly defined.

There is still another important question which such work may aid in solving. It may be stated thus: How much of the water diverted and utilized in the upper valleys returns to the river channel in time to be diverted by lower irrigators? On account of variations in climate, soil, and topography, the results obtained in one section may be worthless when applied to others, and the only way to determine the behavior of irrigating waters is to make the necessary measurements in each valley. Until this work is at least partially accomplished there can be neither a just nor a permanent apportionment of appropriated waters.

The facts upon which this paper is based were obtained during investigations made in the summer of 1896. In this work the writer was ably assisted by Messrs. J. L. Rhead, Thomas H. Humphreys, and John S. Baker. The expenses were borne jointly by the Utah Agricultural Experiment Station, the Division of Hydrography of the United States Geological Survey, and the board of county commissioners of Cache County, Utah. Owing to the large cost of transportation, it was necessary to confine the greater part of the work to Cache County, Utah. In Cache Valley, which comprises the cultivated portions of this county and the southeastern part of Oneida County, Idaho, the field operations consisted in the measurement of every stream flowing into the valley at three different times during the season; also the determination of the capacity of every ditch and canal in the same valley at least three times, and accurate current-meter measurements and daily records of the outflow of the valley through "The Narrows" on Bear River. While this work was in progress an attempt was also

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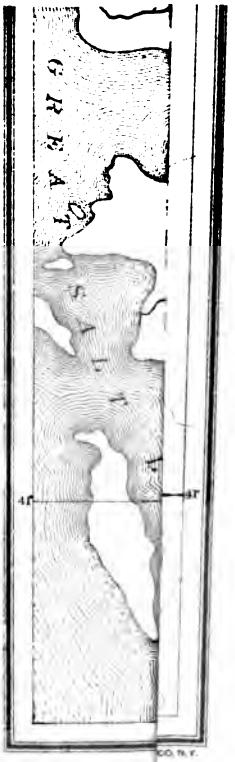

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made to locate the head gate and determine approximately the route of each ditch and canal. The results of such surveys are reproduced in the accompanying map (Pl. I). The progress of the field work throughout the season is fairly well shown by the number of streams and canals measured each month. From June 15 to 30, 1896, there were 58 measurements; in July, 131; in August, 112; in September, 106; and in October, 19; making a total of 426.

The chief object which the writer had in mind in making a partial hydrographic survey of Cache Valley was to determine, if possible, by daily and semiweekly gagings, the ratio existing between the inflow (diminished by the volumes used in irrigation) and the outflow. This ratio being known for a continuous period of three months, an opportunity is afforded to compare the loss of water due to evaporation with the gain due to seepage. Other objects held in view, of minor importance to the student of hydrography but possessing great value to the irrigator, were the average flow of the various ditches and canals, the amount of the surplus waters of the larger streams, and the duty of the irrigating waters.

There are several hundred natural and artificial water channels in Cache Valley if the main laterals are included. It is safe to assert that prior to June 15, 1896, less than six measurements had been made of these canals and streams. This record does not include the work done since 1889 by the United States Geological Survey, which perhaps comprises fifty stream measurements in Cache Valley alone. It was thought that if each canal and small stream were measured first in June, then during the latter part of July, and lastly about September 1, the results of the three measurements would represent, with some exceptions, the greatest, medium, and least flow during the season, and that the average of the three results might be taken as the average flow of such canal or creek.

ORIGIN OF SEEPAGE WATERS.

The water contained in the open spaces occurring in clay, sand, gravel, and other materials of which soils and subsoils are composed, is known by various names, such as soil moisture, ground water, ground storage, subsurface supply, and the like. When this ground water moves down an inclined stratum of porous materials, the term seepage water seems to be more appropriate than that of ground flow, which many writers have recently used. Seepage water conveys the idea of lateral motion, but when one uses the terms "soil moisture," "ground water," or "underground water," this conception is usually not implied.

The water content in dry soils may be so small as to admit of only a slight vertical movement due to the forces of capillarity and evaporation. On the other hand, portions of soils and subsoils may be completely saturated, but so located that the water confined therein

is stagnant. In such cases there can be no lateral flow. Seepage waters as herein defined may be regarded as coming from three sources, which, however, are not always distinct: (1) from uncultivated hillsides and mountain slopes; (2) from irrigated land; (3) from the beds and side slopes of water channels.

It will be readily understood that a complete determination of the quantity of water which comes from that which is stored in the ground, on any particular drainage basin, involves more than a knowledge of the results of the stream measurements made in such basin. It is possible, for example, to ascertain with considerable accuracy the amount of surface water which flows into a valley, the volume used in irrigation, and the outflow, but without knowledge of the losses occasioned by evaporation, the problem of seepage waters is indeterminable. For the want of much necessary information in relation to the precipitation and evaporation of northern Utah, there is herewith introduced in outline some of the more recent observations made elsewhere in connection with the quantities of water evaporated from water surfaces and from ground surfaces or transpired from plant foliage.

In examining the water supply of any section, such as Cache Valley, it is desirable to begin with a study of the rainfall. If the complete history of each raindrop or snowflake were known from the time it falls to the ground until it again returns, in the form of vapor, to the atmosphere, water problems could be readily solved. The total volume of water which falls as rain or snow on any particular watershed may be subdivided into four parts, which vary widely in accordance with local conditions. Of these, one portion runs off the surface and fills the streams, especially during the spring months; a second sinks into the soils and subsoils, enters the fissures of rocks, is absorbed by porous strata, such as sandstones, and is the chief source from which wells and springs derive their supplies and streams their late summer and autumn discharges; a third part of the annual precipitation is evaporated from ground and water surfaces; and the fourth part develops plant growth. From the standpoint of the farmer, that portion utilized in developing plant growth is the most important. Cultivated plants are chiefly dependent on the water which sinks into the ground; hence the importance of the latter to the irrigator.

Relatively too much attention has been given to the surplus flow in springtime and too little to that derived from ground storage. A reference to Logan River may serve to illustrate the difference between that portion of the rainfall which rushes off the surface of drainage basins, either when snow melts in spring or when cloud-bursts occur in summer, and that which sinks into the porous covering of the mountain slopes to issue later as the flow from the ground storage, maintaining the streams during the late summer and autumn months. During June, July, and August of 1893, the rainfall as measured at

the Experiment Station on the basin of Logan River was only one-fourth inch. The snow on the mountain ranges had all melted before the end of July, yet on the 3d of September there was a flow in Logan River of 250 second-feet. Where did this supply come from? The slight rainfall need not be taken into account, for it is safe to assume that an amount many times greater than the rainfall was evaporated. It could not have come from melted snow, because the snow had disappeared as vapor, had run off, or had sunk into the ground long before the expiration of the time named. The only available source was the flow from the ground storage; in other words, the seepage from the mountain slopes.

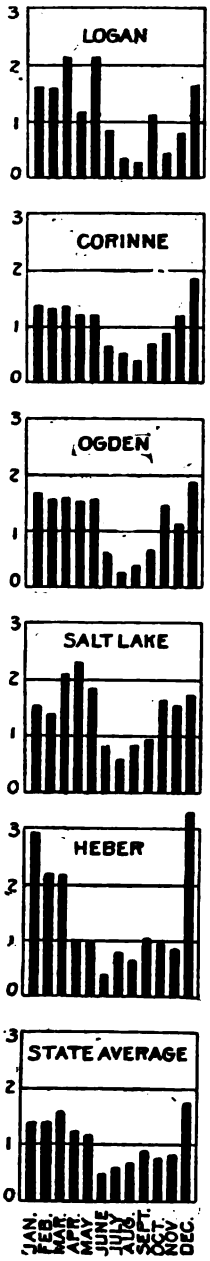

FIG. 1.—Diagram showing mean monthly rainfall in inches at stations in Utah.

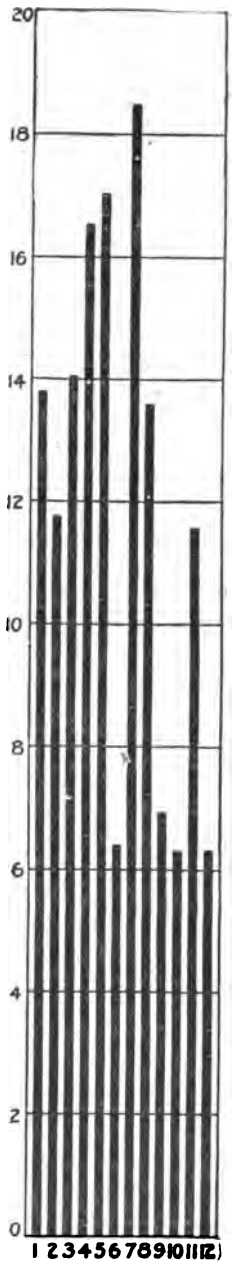

FIG. 2.—Diagram showing mean annual rainfall in inches at 12 stations in Utah.

PRECIPITATION.

The records from a number of important localities where the observations are most reliable have been tabulated by Mr. James Dryden, meteorologist of the Utah Experiment Station. These records extend over past periods varying from three to thirty-three years, and represent quite accurately the precipitation on the valleys and table lands.

The diagrams and tables herein given are compiled principally from information obtained from Mr. Dryden. Fig. 1 is a graphic representation of the precipitation for each month of the year at each of five northern stations. At Corinne, Boxelder County, the month of greatest rainfall for twenty-five years has been December,

averaging 1.8 inches. January, February, March, April, and May have remained nearly constant at about 1.25 inches each, while the dry months have been June, July, August, and September, which have not averaged one-half inch each. This distribution of the annual precipitation is typical of nearly every section of Utah. A glance at the diagrams of fig. 1 is sufficient to show that June, July, August, and September are the dry months, and as these constitute the greater part of the period between seed time and harvest, the rain evidently falls at the wrong time.

Salt Lake County, as represented by the rainfall of the city of Salt Lake, has averaged during the past thirty years 16.53 inches, but during the four summer months, beginning June 1, the total average rainfall has been less than 3 inches. From 1870 to 1895, Weber County, as represented by the station at Ogden, has had an average annual precipitation of 14.02 inches, but the four summer months have not averaged one-half inch. The diagram at the bottom of fig. 1 gives the mean monthly precipitation for the State as obtained by averaging the results of the more important stations scattered in various parts and located at different altitudes. This exhibits the deficient rainfall during June and the gradual increase through July, August, and September. Fig. 2 gives the average annual precipitation at twelve important stations, these being arranged in a general geographic order from north to south, the most northerly being Logan, in Cache County, and the most southerly St. George, in Washington County, in the southwestern corner of the State. The numbers at the bottom of the figure refer to the stations named in the table below.

The following table gives for the 12 selected stations the approximate elevation above sea level, the length of the record in years, and the mean annual rainfall during this time:

Mean annual rainfall at 12 stations in Utah.

No. in diagram.	Place.	County.	Above sea level.	Length of record in years.	Mean annual rainfall.
			Feet.		*Inches.*
1	Logan	Cache	4,500	5	13.81
2	Corinne	Boxelder	4,232	26	11.73
3	Ogden	Weber	4,340	26	14.02
4	Salt Lake	Salt Lake	4,354	33	16.53
5	Heber	Wasatch	5,500	3	16.97
6	Fort Duchesne	Uinta	4,941	8	6.35
7	Levan	Juab	5,100	7	18.45
8	Fillmore	Millard	5,100	8	13.60
9	Moab	Grand	3,900	7	6.95
10	Loa	Wayne	6,900	4	6.28
11	Parowan	Iron	5,970	5	12.55
12	St. George	Washington	2,880	15	6.31

Below is given the mean monthly rainfall for the same period:

Mean monthly precipitation at twelve stations in Utah.

Place.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Logan	1.55	1.52	2.05	1.12	2.06	.78	.27	.21	1.60	.36	.74	1.55
Corinne	1.27	1.26	1.29	1.12	1.12	.58	.44	.31	.63	.84	1.07	1.80
Ogden	1.65	1.51	1.57	1.47	1.49	.58	.25	.40	.68	1.42	1.12	1.88
Salt Lake City	1.46	1.31	2.01	2 24	1.76	.78	.55	.75	.91	1.60	1.48	1.68
Heber	2.89	2.16	2.15	1.01	.95	.35	.75	.61	1.08	.94	.80	3.28
Fort Duchesne	.38	.50	.71	.77	.79	.25	.48	.63	.60	.24	.23	.77
Levan	1.63	1.83	2.33	2.22	2.07	.69	.40	.77	1.39	1.04	.76	3.32
Fillmore	1.47	1.68	1.65	2.25	1.11	.53	.51	.83	.98	.45	.73	1.41
Moab	.68	.73	.86	.32	.33	.08	.64	.51	.72	.42	.59	1.07
Loa	.57	.74	.63	.15	.33	.08	.87	1.08	.49	.46	.43	.45
Parowan	1.27	1.56	2.03	1.35	.95	.17	1.09	1.06	1.04	.71	.57	1.00
St. George	1.01	.91	.60	.27	.33	.03	.33	.29	.41	.31	.44	1.38

More than the usual amount of rain fell in Cache Valley during 1896, as shown by the following table, which gives the precipitation for June, July, August, and September of that year, and also the averages of all past records for the same months:

Precipitation at Logan, Utah, for four months.

	1896.	Prior to 1896.
	Inches.	*Inches.*
June	0.46	0.78
July	1.40	0.27
August	1.49	0.21
September	0.91	1.60
Total	4.26	2.86

EVAPORATION.

Many tests have been made in different parts of the world to ascertain the amount of water evaporated from water surfaces. The utilization of this information is, however, limited chiefly to hydraulic engineers who wish to determine the losses from reservoir and lake surfaces. A knowledge of the actual volumes of water evaporated from such surfaces is of little direct value to Western irrigators, for the reasons that the operating forces are entirely beyond their control and the evaporated water is borne away by the prevailing winds. It might be some satisfaction to know that the evaporation from the surface of Great Salt Lake was only 60 inches yearly instead of 80 inches, as some would have us believe; but that knowledge alone might not enable us to reclaim an additional acre of land in Utah, although the difference of 20 inches yearly over the entire surface of the lake would

comprise a volume of water sufficient to irrigate a million acres. There is good reason to believe that little of the moisture withdrawn from the Utah lakes returns in the form of rain or snow within the confines of the State. Tooele County borders on Great Salt Lake, but with a probable annual evaporation of 6 feet near its shore line, the parched soil receives yearly on an average only about 6 inches from rainfall.

Comparatively few measurements of evaporation have been made in Utah. The most important were those carried on at the reservoir in the rear of Fort Douglas, immediately east of the city of Salt Lake.

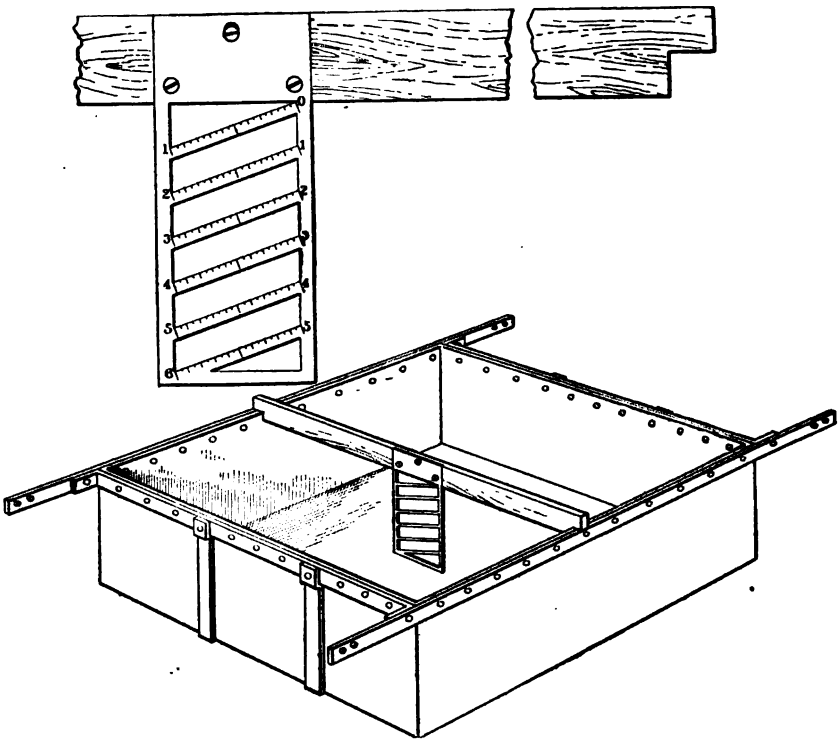

FIG. 3.—Evaporating pan and scale.

These observations are mentioned in the Eleventh Annual Report of the United States Geological Survey, Part II, on pages 30 to 34, and the results are given briefly in the Fourteenth Annual Report, page 154. Similar measurements were made for a few months at Provo and Nephi.

The apparatus used by the Geological Survey in making observations of evaporation consists of a galvanized-iron pan 3 feet square and 10 inches deep, immersed in water and kept from sinking by means of floats of wood or hollow metal. Into this pan water is poured until the surface is within from 1 to 2 inches of the top, the attempt being

edge. The temperature of the water inside the pan has been found by experience to be practically uniform with that of the surrounding water in the ditch or pond in which the pan is placed, varying from it usually not more than 1 or 2 degrees. If the pan is kept full, so that the edge or rim does not offer an obstruction to the wind, the evaporation from the surface inside the pan should be approximately the same as that from the surface of the water outside.

The amount of water evaporated is determined by measuring the decrease in height of water, observations being usually taken once or sometimes twice a day. These are made by means of a brass scale hung in the middle of the pan and provided with diagonal bars upon which the reading is magnified about three times. By the use of this scale it is possible to read differences in vertical height of one one-hundredth of an inch. This method of observing the height of water is probably not so good as that by means of a hook gage, but is somewhat simpler and the apparatus is less expensive. An improvement[1] has been proposed, consisting of a rod fixed rigidly in the center of the pan and rising to within 1 or 2 inches of the top. Water is put into the pan until the point of this rod is about to be submerged, as shown by the meniscus. As the water evaporates more is added by means of a tin cup made of such capacity that one cupful is equivalent to a depth of one one-hundredth of an inch on the surface of the pan. The observer has only to record the number of times the cup is filled and emptied into the pan.

The following table gives the results of the measurements at Fort Douglas, the observations beginning on August 23, 1889, and ending in May, 1893. They were made by a soldier, Charles M. Lowry, detailed for the purpose. Owing to numerous disturbing influences, such as heavy wind splashing water into the pan or rainfall adding to the quantity, or, during winter, the freezing of the surface, it was rarely possible to continue observations consecutively for more than a few days at a time. The table gives, therefore, the number of days in each month during which fairly reliable results were obtained, and also the average of these daily observations. This average is assumed to be that for all the days of the month, and is therefore multiplied by the number of these to obtain the approximate monthly total.

[1] Physical data and statistics of California, 1886, p. 373.

Evaporation at Fort Douglas, Utah, in inches.

Month.	1889.			1890.			1891.			1892.			1893.		
	Days.	Mean daily.	Total.	Days.	Mean daily.	Total.	Days.	Mean daily.	Total.	Days.	Mean daily.	Total.	Days.	Mean daily.	Total.
March	----	------	------	----	------	------	----	------	------	15	.067	2.1	----	------	------
April	----	------	------	----	.123	3.7	19	.107	3.2	14	.075	2.3	3	.083	2.5
May	----	------	------	----	.133	4.1	15	.153	4.8	----	.132	4.1	8	.169	5.2
June	----	------	------	----	.170	5.1	22	.174	5.2	25	.177	5.3	----	------	------
July	----	------	------	16	.240	7.6	10	.246	7.6	26	.211	6.5	----	------	------
August	11	.340	10.5	20	.210	6.5	20	.210	6.5	10	.235	7.3	----	------	------
September	18	.190	5.7	23	.153	4.6	17	.174	5.2	25	.174	5.2	----	------	------
October	7	.157	4.9	21	068	2.1	15	.081	2.5	15	.068	2.1	----	------	------
November	2	.065	1.0	18	.041	1.2	15	.047	1.4	10	.055	1.6	----	------	------

Observations were conducted in a similar manner at Provo during a portion of the month of October, 1889, giving an average daily evaporation of 0.10 inch, and at Nephi, at intervals during a part of the same year, giving a mean daily evaporation for June of 0.13 inch; for July, 0.16 inch; for August, 0.15 inch, and for September, 0.10 inch. Similar fragmentary results have been obtained for localities in other parts of the West.[1] The longest series, however, is that begun in 1887 by Prof. L. G. Carpenter at the Experiment Station at Fort Collins, Colorado. The evaporating pan at this place is 3 feet square and 3 feet deep, sunk into the ground, the height of water being measured by means of a hook gage. The results have been published only up to the end of 1891.[2]

Monthly evaporation at Fort Collins, Colorado, in inches.

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Total.
1887	2.46	3.23	4.60	5.55	5.19	5.75	5.23	4.24	4.12	3.26	1.48	1.60	46.71
1888	------	------	------	------	4.45	7.70	7.00	4.06	3.94	2.17	1.35	0.99	------
1889	1.09	1.06	2.75	4.06	3.72	4.34	5.20	5.15	5.19	3.28	0.62	1.42	37.83
1890	0.86	2.36	3.48	3.50	4.32	5.71	5.44	5.76	3.69	2.71	1.32	1.10	40.24
1891	1.20	2.79	2.23	2.24	5.06	4.97	5.72	4.90	4.12	3.62	1.73	0.75	39.12

At the experiment station located at Laramie, Wyoming, Prof. J. D. Conley noted a total evaporation from April 17 to October 22, 1895, of 37.02 inches, distributed as follows: April 17–30, 2.53; May, 7.33; June, 6.24; July, 7.29; August, 6.07; September, 4.94; October 1–22, 2.62 inches. In this test the evaporation was measured by means of a hook gage within a tank lined with galvanized iron, and holding when full a cubic meter of water.[3]

Prof. T. Russell, in the Monthly Weather Review for September,

[1] Eleventh Ann. Rept. U. S. Geol. Survey, Part II, p. 34.

[2] Fourth Ann. Rept. State Agricultural Experiment Station, Fort Collins, Colorado, 1891, p. 53.

[3] University of Wyoming Experiment Station Bulletin No. 27, March, 1896, Meteorology for 1895, p. 15.

1888, gives the results of one year's observations, from July 1, 1887, to June 30, 1888, of the Piche evaporometer.

From this article are obtained the following figures, which give the computed evaporation in inches at several points:

Estimated depth of evaporation in inches.

Station.	Jan.	Feb.	March.	April.	May.	June.	July.
Salt Lake, Utah	1.8	2.7	3.6	7.2	6.9	8.9	9.2
Boise City, Idaho	1.6	2.5	3.8	6.1	6.5	6.6	10.0
Winnemucca, Nev	0.9	2.8	6.2	9.1	9.3	10.1	11.5
Denver, Colo	2.8	3.7	3.5	7.6	5.8	10.5	8.3
Cheyenne, Wyo	3.3	5.7	4.0	8.2	5.2	10.4	8.0
Helena, Mont	1.1	3.6	2.1	6.1	4.3	5.5	7.2
Santa Fe, N. Mex	3.0	3.4	4.2	6.8	8.8	12.9	9.2
Yuma, Ariz	4.4	5.2	6.6	9.6	9.6	12.6	11.0

Station.	Aug.	Sept.	Oct.	Nov.	Dec.	12 mos. evaporation.	Precipitation in 1888.
Salt Lake, Utah	10.7	9.6	6.5	5.0	2.3	74.4	13.62
Boise City, Idaho	9.2	7.4	5.2	3.2	1.8	63.9	11.09
Winnemucca, Nev	12.0	9.9	6.6	3.7	1.8	83.9	4.89
Denver, Colo	8.5	6.1	4.9	4.2	3.1	69.0	9.51
Cheyenne, Wyo	7.7	8.6	5.8	6.1	3.5	76.5	14.51
Helena, Mont	7.7	6.4	4.3	3.0	2.1	53.4	10.14
Santa Fe, N. Mex	9.8	6.6	6.7	5.7	2.7	79.8	12.03
Yuma, Ariz	10.2	8.2	8.2	5.5	4.6	95.7	2.95

An estimate of the total amount of yearly evaporation from water surfaces in this State, based on the foregoing facts, would vary from 3 to 6 feet in depth, depending upon the temperature, frequency, and velocity of the winds, dryness of the atmosphere, and like conditions. From the same data we may conclude that, generally speaking, the evaporation during the four months of May, June, July, and August, or, in other words, the irrigation period of this section, is equal to that of the remaining eight months.

The comparatively large loss by the yearly evaporation from wet ground surfaces of the Western States is of far greater importance than the evaporation which takes place at water surfaces, for the reason that, in a measure, it can be controlled by man. Such conservation of the obtainable water supply results in having available a balance which can be utilized in reclaiming desert land and in increasing the productions of land now cultivated.

One of the cheapest and most effective methods of checking excessive evaporation is cultivation. In this regard Utah irrigators have an important lesson yet to learn. The custom of the majority is to apply large quantities of water to growing crops, making a paste of the top soil. In less than twenty-four hours the water in this top layer is evaporated, leaving the ground hard and baked. Under such

conditions it is astonishing how rapidly the soil moisture is evaporated. If this top crust is left undisturbed for a few days, the soil becomes parched, the crops apparently suffer for lack of moisture, and the unskilled irrigator fancies the only remedy is to apply more water.

With the most careful attention while irrigating, it is not possible always to prevent the formation of paste by the mixture of fine soil and water and the subsequent baking; but the robbing the soil of its moisture through excessive evaporation can be avoided by breaking up the surface crust as soon as it forms and by keeping the surface layer thoroughly pulverized, thus effectively checking evaporation in even the hottest weather.

Recent experiments have shown that evaporation from the surface of soil can be greatly decreased by mulching. The effect, for example, of a 3-inch layer of broken, compacted oat straw, spread evenly over the surface of a strawberry field in Minnesota, was to decrease the evaporation by 605 barrels per acre, and the gain in moisture to the soil of a vineyard by a similar treatment was 1,600 barrels per acre, sufficient to cover the entire surface to a depth of nearly 2 inches.[1]

It has been repeatedly demonstrated that wind is a prime factor in increasing evaporation from both ground and water surfaces. While it is true that the frequency, course, and velocity of the winds lie beyond the control of the agriculturist, yet by planting suitable trees to form wind-breaks within and around cultivated fields, much benefit may be gained. The foliage of the trees will decrease the temperature, increase the humidity of the air, and break the force of the wind.

Perhaps the most complete test of the amount of water evaporated from soil and water surfaces was made in England by Charles Greaves,[2] M. Inst. Civ. Eng. His results are summarized by Fanning as follows:

The mean annual rainfall during the time (1860 to 1873) was 27.7 inches. The annual evaporations from soil were—minimum, 12.07 inches; maximum, 25.14 inches, and mean, 19.53 inches; from sand—minimum, 1.43 inches; maximum, 9.10 inches, and mean, 4.65 inches; from water—minimum, 17.33 inches; maximum, 26.93 inches, and mean, 22.2 inches.[3] The climatic conditions of arid America are so unlike those of England that the above results do not in the least apply. They show, however, that, other conditions being equal, the amount of evaporation from ground surfaces is somewhat less than from water surfaces.

Dr. E. Wollny of Munich confirms this view when, in summarizing the work of three years on evaporation from land surfaces, he concludes:[4]

(1) That the quantity of moisture evaporated from the soil into the atmosphere is considerably smaller than that evaporated from a free surface of water.

[1] Bulletin No. 32, Minnesota Agricultural Experiment Station.

[2] Trans. Inst. Civ. Eng., Vol. XLV, pp. 3-29.

[3] A Treatise on Hydraulic and Water-Supply Engineering, by J. T. Fanning, 1889, p. 90.

[4] Prof. E. Wollny, Forschungen, Vol. XVIII, p. 486. Abstracted in the Monthly Weather Review, Department of Agriculture, November, 1895, p. 422.

(2) That the evaporation is smallest from naked sand, and largest from naked clay, whereas naked turf and humus or vegetable mold have a medium value.

(3) That the evaporation is increased to a considerable extent by covering the ground with living plants.

(4) Evaporation is a process that depends upon both the meteorological conditions and on the quantity of moisture contained by the substratum of soil.

(5) Among the external circumstances, temperature is of the greatest importance, inasmuch as, in general, evaporation increases and diminishes with it; but this effect is modified according as the remaining factors come into play and in proportion to the quantity of water supplied by the substratum.

(6) The influence of higher temperature is diminished more or less by higher relative humidity, greater cloudiness, feebler motion of the wind, and a diminished quantity of moisture within the soil, whereas its influence increases under opposite conditions.

On the other hand, low temperatures can bring about greater effects than high temperatures, if the air is dry, or the cloudiness small, or the wind very strong, or if a greater quantity of water is present within the evaporating substance.

(7) For the evaporation of a free surface of water, or for earth that is completely saturated with water, the important elements are, first, the temperature; next, the relative humidity of the air, and then the cloudiness and the direction and velocity of the wind; whereas, for the ordinary moist earth, no matter whether the surface is naked or covered with living plants, it is the quantity of rain upon which the soil depends for its moisture that is the important additional consideration. The effects of the external elements on evaporation become less important, as explained in paragraph 5, in proportion as the precipitation is less and as the soil is more completely dried out by the previous favorable weather, and vice versa. For these reasons the rate of evaporation from a free surface of water not infrequently differs largely from that from the respective kinds of soil.

(8) Free surfaces of water and soils that are continuously saturated evaporate into the atmosphere on the average more water under otherwise similar circumstances than soils whether naked or covered with plants and whether watered artificially or naturally. Only at special times, viz, when the influence of the factors that favor evaporation is most intense, when the plants are in the most active period of growth, and when the soil contains a large percentage of water, can the land that is covered with plants show larger evaporating power than the free water surface.

(9) When a soil that is not irrigated is covered with plants, it evaporates a far greater quantity of moisture than when the surface is bare. In the former case the evaporation can not exceed the quantity received by the soil from the atmosphere before or during the period of growth. Swampy lands and those that are well irrigated, as also free surfaces of water, can, under circumstances favorable to evaporation, sometimes give to the atmosphere a greater quantity of water than corresponds to the precipitation that occurs during the same time.

(10) The evaporating power of the soil is, in itself, dependent upon its own physical properties; the less its permeability for water, or the larger its capacity for water and the easier it is able to restore by capillarity the moisture that has been lost, by so much the more intensive is the evaporation. For this reason the quantity evaporated increases with the percentage of clay and humus in the soil, whereas it diminishes in proportion as the soil is richer in sandy and coarse-grained materials.

(11) Soil that is covered with plants loses by evaporation so much more water in proportion as the plants are better developed, or stand thicker together, or have a longer period of vegetation, and vice versa.

In the above summary Dr. Wollny touches upon various phases of evaporation which have an important bearing on Western irrigation. At present there is little data to enable us to compare intelligently the results obtained in Germany with those in this country. However, some of the Agricultural Experiment Stations are taking up this work, and in a few years we may hope to know much more of the behavior of soil moisture and ground waters and their relation to plant life. The main object to be attained in the artificial application of water to soil is to develop plant life, and as this can be accomplished only by creating a moist soil and subsoil, it is necessary that we endeavor to ascertain the greatest possible percentage of the total precipitation that can be used for this purpose. In this State evaporation from both water and land surfaces must be regarded as one of the chief sources of waste, and as such deserving of careful study.

TRANSPIRATION.

In arid America agricultural products are almost entirely dependent upon the water supply. As a rule, the soil is fertile, containing in abundance the elements necessary for the development of plants; but if the water supply be either deficient or applied at the wrong time, a partial growth will result. The portions of a wheat field that are missed at the first irrigation seldom yield one-third of a crop. These dry places may be irrigated subsequently, but the second watering can not restore the shrunken cellular tissues nor the lost vigor. The skilled horticulturist has learned by experience and observation how and when to irrigate his fruit trees. When the trees are young, water is conveyed in two furrows only, one on each side the row of trees and at some little distance beyond the farthest roots. As the tree grows, the roots thrust themselves farther into the soil, but chiefly in the direction of the water supply, and in the following season the two furrows may be increased to four, until finally, in well-matured trees, all the space of 20 feet or more between the rows is thoroughly watered. By such a method water is not only provided for the soil, but is applied in such a way as to lead out the roots in quest of moisture and food.

Much has been written recently on subirrigation, and many agricultural experiment stations have gone so far as to pronounce this method superior to all others. By it water is conveyed through pipes buried in the ground and is discharged through a large number of small holes located opposite each tree. This mode of irrigation has not been successful. In the first place, it is an impossibility to cause water to discharge equally through so many orifices; and in the second place, the water is deposited at particular points in the soil, around which the roots of plants are sooner or later massed. The few advantages to be gained by applying the water beneath the sur-

face can not be compared to the disadvantages due to the difficulties in the way of its distribution and to the concentration of the roots at particular places.

The injurious effects upon vegetation caused by either too little water or too much are clearly illustrated by the results of experiments made by Dr. E. Wollny[1] on summer rape, as given in the following table. In this, the first column gives the per cent of water in the soil as compared to the total water-holding capacity. The second column gives the number of pods produced, and the following columns give the weight of the various parts:

Effect of excess and deficiency of moisture.

Per cent of water in the soil.	Number of pods.	Weight of plants air-dried.			
		Seed, in grams.	Straw, in grams.	Chaff, in grams.	Total, in grams.
10	43	1.4	2.8	1.4	5.6
20	61	2.4	4.4	2.6	9.7
40	142	6.9	10.4	6.7	24.0
60	97	4.3	8.1	4.4	16.8
80	95	3.9	7.3	3.9	15.1
100	19	0.3	2.0	0.6	2.9

In growing plants in pots it is possible to apply just the right amount of moisture, but on the irrigated field it is somewhat different. At each watering the ground is for a time nearly saturated. Part of this excess water is soon evaporated, either from the ground or indirectly through the foliage. Another part sinks into the subsoil, and the remainder keeps the soil moist. If this soil moisture can be maintained in the right proportion, or, in other words, if the amount drawn from the subsoil by capillarity equals the loss by evaporation until the next watering, the crop will grow under the most favorable conditions as regards moisture. If too little water is applied to the surface and the subsoil water for some cause is inaccessible, the crop will suffer and become more or less dwarfed. On the other hand, too much water may keep the soil near the extreme of complete saturation and produce upon vegetation as harmful effects as too dry a soil. A cubic foot of average soil when thoroughly saturated will contain from 25 to 30 pounds of water. According to Wollny's experiment, the best results were obtained on summer rape when about 40 per cent of the empty space in the soil was filled, which would be equivalent to from 10 to 12 pounds of water in every cubic foot of soil.

We may thus classify productive soils under three heads in relation

[1] Experiment Station Record, Vol. IV, p. 532.

to the percentage of moisture which each contains, viz, as dry soils, moist soils, and wet soils. It may also be said that in each of these classes the amount of water drawn up by the roots and transpired by the leaves differs. The magnitude of this transpiration of vapor through the foliage of plants has been investigated by Messrs. King, Wollny, Hellriegel, and others, the results of whose labors are briefly summarized in the following tables:

Amount of water required for a pound of dry matter in Wisconsin.[1]

Crop.	Year.	Water per pound of dry matter.	Yield per acre, pounds.	Water per acre, inches.
Barley	1891	402	7,441	13
Do	1892	375	14,196	23
Oats	1891	501	8,861	20
Do	1892	525	8,189	19
Corn	1891	301	19,845	26
Do	1892	316	19,184	25
Clover	1892	564	12,486	30
Pease	1892	477	8,017	17

Ratio of water evaporated to weight of crop harvested, as shown by experiments of Hellriegel and Wollny.[2]

Crop (Hellriegel).	Water evaporated.	Crop (Wollny).	Water evaporated.
Horse beans	262	Maize	233
Pease	292	Millet	416
Barley	310	Pease	447
Clover	330	Sunflower	490
Spring wheat	359	Buckwheat	646
Buckwheat	371	Oats	665
Lupine	373	Barley	774
Spring rye	377	Mustard	843
Oats	402	Rape	912

According to Hellriegel, as shown by the above table, 330 tons of water would be absorbed by the roots of clover, drawn up through the stems, and evaporated from the breathing pores of the leaves, for each ton of clover harvested. If the yield be estimated at 3 tons per acre, the quantity of water per acre is 990 tons, or a volume sufficient to cover the surface to a depth of nearly 9 inches. So far as has been ascertained, no tests have been made in the Rocky Mountain region

[1] F. H. King, Agricultural Experiment Station, University of Wisconsin, Ninth Annual Report, 1892, p. 94.

[2] Department of Agriculture, Experiment Station Record, Vol. IV, p. 532.

of the amount of water actually consumed by the various agric crops between the time of germination and the harvest, but ob facts seem to indicate that this amount varies with the conditi soil moisture.

In sections of northern Utah, where water can not be rea cheaply conveyed to irrigate the land, the fields are usually s wheat and cultivated "dry," the annual yield being from 1 bushels per acre. During the period of growth the rainfall i sionally less than 1 inch, and the soil and subsoil apparently a dry. If the quantity of water consumed by the wheat was eve third of that given by Prof. F. H. King for barley and oats, averaged a depth of nearly 19 inches over the entire surface vated, it is difficult to conjecture where the supply could come

On irrigated lands the case is quite different. The proper a of moisture is maintained in the soil, the plant is kept in a h vigorous condition, and the normal amount of water passes th its tissues, bearing the necessary mineral food furnished by th It is not unusual to irrigate alfalfa every other week, and to an amount of water over the surface during its period of growt cient to cover the ground to a depth of 6 feet. A part of the used in irrigating usually sinks into the subsoil and flows off a age water, a second part is evaporated, and the third part, p one-third of the whole supply, passes through the tissues of the and is mostly transformed into vapor at the leaves.

The sagebrush and grasses indigenous to the uncultivated of the Rocky Mountain region require but little moisture to ma their slow growth. In the vicinity of Corinne, Boxelder C Utah, the average annual rainfall for the past twenty-five yea been less than 12 (11.73) inches. Little snow remains for any of time on the ground; the evaporation in summer is excessive moist ground and water surfaces; and yet sagebrush flourishes, ing to a height of from 3 to 5 feet. If we deduct from the total precipitation the probable amount of moisture evaporated, ver will remain for the use of the plants. It is possible that the quantity of water absorbed by the roots of the plants that g uncultivated lands and transpired by their foliage does not e one-tenth of the annual precipitation, which in this State wo about 1¼ inches over the surface of unreclaimed arable lands. preceding estimates, based on observed facts, we may therefor clude that in this State the amount of water evaporated from th age of plants ranges from a surface depth of 1 inch for buffalo and sagebrush to a surface depth of 20 inches for well-irrigated a

CACHE VALLEY.

This beautiful valley is nearly surrounded by mountains. of the Wasatch Range forms the elevated divide between it an Lake Valley, in Rich County, to the east, and another spur

same range forms the lower divide between it and Great Salt Lake and Malad River valleys to the west. The average elevation of the cultivated portion of the valley is about 4,500 feet. Its length from north to south varies from 40 to 50 miles, and its width from east to west from 10 to 15 miles.

The first white men who wintered in the valley were the Garr brothers. They were engaged by the authorities of the Mormon Church during the winter of 1855–56 to look after the range cattle owned by that church, and they built a rude log hut in the vicinity of what is now the church farm. In the summer of 1858 several families from Brigham reached the valley through Boxelder Canyon and made a permanent settlement in what is now Wellsville.

According to the latest report of the Utah statistician, the population of Cache County in March of 1895 was 18,286. The principal towns and cities in the order of population are: Hyde Park, 647 inhabitants; Providence, 944; Lewiston, 969; Richmond, 1,295; Wellsville, 1,390; Smithfield, 1,448; Logan, 5,756; total, 14,249.

Cache County contains an area of 697,600 acres, of which 30,923[1] acres were irrigated in 1889, and 38,430[2] acres in 1894. From information collected during the past season, supplemented by the records obtained by C. D. W. Fullmer, county statistician, the following table has been prepared, giving the approximate number of acres irrigated for each kind of crop in 1896.

Approximate area irrigated in 1896.

	Acres.
Cereals	20,000
Lucern, hay, etc	15,000
Potatoes, beets, etc	1,500
Fruit trees	1,200
Small fruits	25
Other products	900
Total	38,625

The water utilized in irrigating the southern end of the valley is diverted chiefly from New Canyon, Little Bear, and Blacksmith Fork streams. Logan River, with Summit, High, and Clarkson creeks, furnish the supply for the middle portion. Cub and Weston creeks are the chief sources of supply for the northern portion. Surveys for irrigating canals have been made to divert water from Bear River, in Cache Valley, but owing to the lengths of the proposed canals and the cost of construction, none has yet been built.

The soil in the cultivated portions of the southern end of the valley, and particularly in the vicinity of the towns of Paradise, Hyrum, and Millville, consists for the most part of a rich, black, clayey loam. In the western part clay, with occasional patches of alkali, predominates.

[1] Eleventh Census, Agriculture by Irrigation, F. H. Newell.
[2] First Triennial Report of the Bureau of Statistics of Utah.

The soil in the northern and northwestern por
from coarse gravel to fine sand and clay. O
designated as a soil well adapted for the produ

LOGAN RIVER.

The greater part of the drainage basin of L
mountain range east of Cache Valley. The ma
is quite small, and heads high on the range ab
mountains; but as it flows down a steep chann

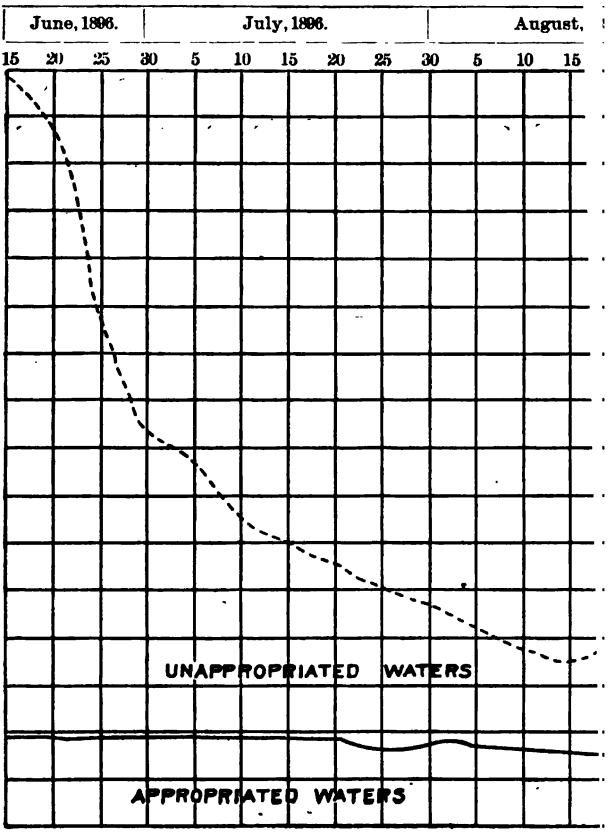

FIG. 4.—Diagram showing appropriated and unappropriated

waters mingle with those from Temple Fork,
Spring Creek, Ricks Spring, and Right Hand
when united, form one of the most important
From its head waters to where it unites with B
miles, only 10 of which lie outside rugged canyo

About the 1st of June, 1896, a permanent gagi
lished on this river a short distance below the n

and above all the canals save one, the Logan, Hyde Park and Smithfield. From daily river-height observations and several current meter measurements the flow has been accurately determined throughout the season. The waters used for beneficial purposes have also been determined by a series of measurements of each canal, and both results are represented graphically in fig. 4. The aggregate volume of all the canals is nearly 200 second-feet; and as the discharge of the river at the mouth of Logan Canyon during a dry season may be less than that amount, the apparent large surplus of last summer, which averaged during the month of August, 1896, 222 second-feet, is not to be depended upon.

Irrigating canals diverting water from Logan River.

Name of canal or ditch.	June.		July.		August.		September.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
Logan, Hyde Park, and Smithfield Canal	12	34.5	21	47.5	31	30.1		
Logan and Richmond Canal	12	60.4	21	69.1	31	50.1		
Providence Canal	12	5.4	21	8.2			1	5.2
Logan, Hyde Park, and Thatcher Canal	12	*a* 48.9	21	*27.0	31	27.5		
Nursery Canal			21	2.4			1	0.7
Logan and Benson Ward Canal	12	*a* 25.0	21	23.9			1	19.3
West Field or Little Ditch			21	11.6			1	7.5

a Estimated.

The Logan, Hyde Park, and Smithfield Canal was completed in June, 1882. Its head gate is located about 1½ miles above the mouth of the canyon, and at an elevation of 326 feet above the business center of Logan City. In July, 1892, the writer, as the consulting engineer of the city corporation, advised the abandonment of the old source of supply, and recommended that the future source be the Logan, Hyde Park, and Smithfield Canal, until funds were available to extend the conduit to the river. Logan City now gets its domestic water supply from that canal, and owns 26⅔ per cent of its paid-up capital stock. The canyon portion of the canal was never properly constructed, and the loss through leakage is very great. On August 31, 1893, the discharge at the head gates, as measured by the writer, was 48 second-feet. At a point 7,000 feet lower down the volume had been decreased, on account of waste, to 26.7 second-feet, a loss of 21.3 second-feet, or 44 per cent of the volume diverted. The area irrigated since 1892 has not varied to any appreciable extent, and the following table gives the figures for the three preceding years:

Area irrigated by Logan, Hyde Park, and Smithfield Canal.

Year.	Farm lands.	City lots.	Total.
	Acres.	*Number.*	*Acres.*
1890	2,184	*a* 63	2,310
1891	2,409	163	2,735
1892	2,785	169	3,123

a A city lot is equivalent to 2 acres of farm land.

The Logan and Richmond Irrigating Company was organiz November, 1864, and the canal was built in 1865–1867. The re of the company show that the land irrigated by this canal in 187 1,400 acres of farm lands and 195 city lots, but the capacity o canal was considerably increased in 1881, and more land was recla at its lower terminus in the vicinity of the town of Smithfield. areas irrigated by this canal in 1895 are as given below:

Area irrigated by Logan and Richmond Canal.

Precinct.	Farm lands.	City lots.	Total.
	Acres.	*Number.*	*Acres.*
Logan	897	214	1,325
Hyde Park	610	50	711
Smithfield	1,240	0	1,239
Total	2,747	264	3,275

Providence Canal is the only irrigating system of any consider size which diverts water from the south or left bank of Logan R It was begun in 1866, but owing to the fact that the locating engi set pegs on an ascending grade from the proposed place of divers and the water would not flow uphill, the enterprise was abando until 1883, when the necessary changes in the elevations were m and the canal completed. The cost of maintenance has always l high, owing to faulty location and steep hillsides, averaging al $250 per annum, and the area irrigated since 1883 has not varied from 300 acres.

Logan, Hyde Park, and Thatcher Canal was begun in the sprin 1860. It is the oldest in Cache Valley, and was the first to di water from Bear River or its tributaries. The primary object hel view by the original projectors was to irrigate wheat lands, but sev mill owners obtained permission to widen the canal sufficientl furnish them with a supply for power purposes. A portion of flow has been so employed ever since, but the tail water from the n

is nearly all subsequently used in irrigation. The canal branches at Sixth street, the upper branch extending to Hyde Park, the lower to a portion of Logan City. The acreage irrigated in 1860 was about 700 acres, and there has been a nearly uniform increase from that time to the present. Of late years the total number of acres irrigated by both branches of the canal has averaged about 2,115, of which 1,215 acres are located in Hyde Park and the remainder in Logan.

Logan and Benson Ward Canal has its headgates near the business center of Logan. The date of its water appropriation extends back to 1861. The extent of land at present irrigated by this canal includes 856 acres in Benson Ward and 2,150 acres in Logan precinct.

West Field, or Little Ditch, takes its supply from the tailraces of the mills and from Logan River at the city park. The first branch was made in the spring of 1860. The ditch flows into Spring Creek pond and receives a portion of its supply from this last source. The area irrigated in late years is 1,100 acres.

The average combined capacity of the 6 canals enumerated above was, for June, 1896, 188.8 second-feet; for July, 183.3 second-feet; for August, 157.6 second-feet; and for September, 131.5 second-feet. Comparing this with the aggregate area irrigated—12,920 acres—it appears that the duty of water per second-foot in June was 68.4 acres; in July, 70.4 acres; in August, 81.9 acres; and in September, 98.3 acres.

BLACKSMITH FORK RIVER.

This stream rises in a range of the Wasatch Mountains which separates Cache Valley from Rich County, flows in a northwesterly direction, and empties into Logan River. Its total length is about 35 miles. The average depth of compacted snow near the sources of this stream in February and March is about 4½ feet, and as the greater part of this snow melts during the month of May and the early part of June, the spring floods are excessive in proportion to the comparatively small area drained.

The discharge of this stream at a point a short distance below the mouth of Blacksmith Fork Canyon from June 15 to September 15, 1896, and the combined flow of all the irrigating canals diverting water therefrom are represented graphically in fig 5. The maximum volume of water appropriated and utilized is therein shown to be 180 second-feet, while the discharge of the stream may be said, if we except a few days in September, not to fall below that amount during the irrigating period.

As shown by the following table, six canals divert water from this source and vary in carrying capacity from 4 to 70 second-feet. The Hyrum Canal is the largest and is divided near its head gates, the upper branch supplying water to a portion of Hyrum City, and the lower being used on the fields adjacent to Millville. Solveson & Co.'s

ditch is one of small capacity, and waters the lands on the river bottoms. The remaining four canals extend to the town of Millville and its vicinity, two being taken out on the east side of the river and two on the west.

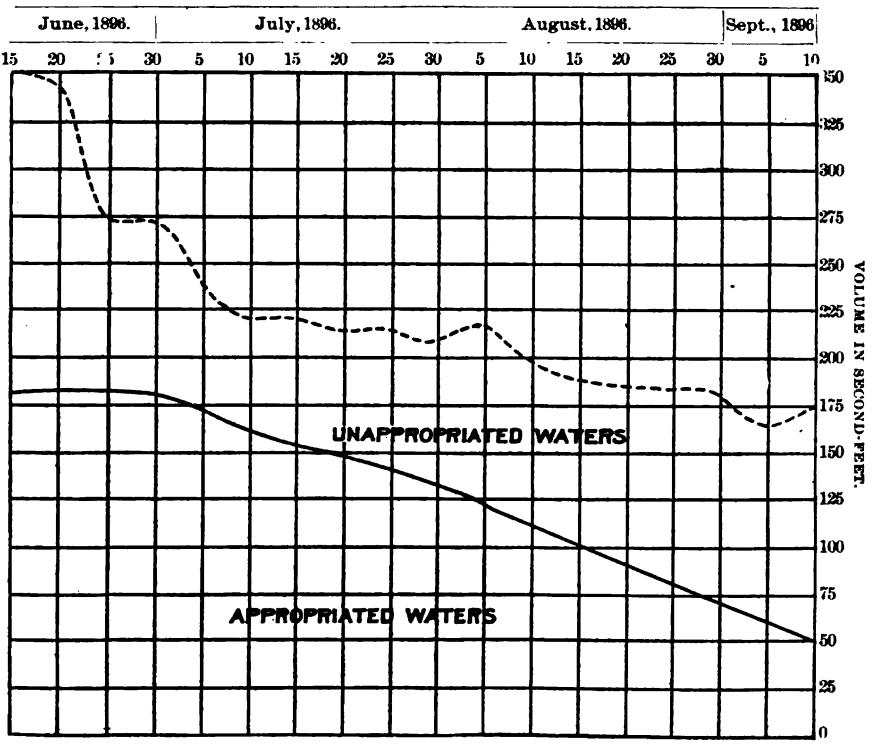

FIG. 5.—Diagram showing appropriated and unappropriated waters of Blacksmith Fork River.

Irrigating canals diverting water from Blacksmith Fork River.

Name of canal or ditch.	June.		July.		August.		September.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
Solverson & Co.'s ditch	18	3.9	9	0.8	5	2.2	15	Dry.
No. 1 canal	18 29	27.8 32.9	10	17.4	4	22.8	15	4.3
Hyrum canal	18	48.7	10	63.6	4	65.9	15	22.8
No. 3 canal	18	70.6	10	51.7	4	26.1	15	11.2
No. 2 canal			9	16.4	4	6.7	15	3.4
No. 4 canal			9	13.5	4	1.1	15	Dry.

LITTLE BEAR RIVER.

Little Bear River, Little Muddy River, or Boxelder Creek, as it is variously termed, is a tributary of Logan River. It is formed by two main streams which unite near the town of Paradise, in the southern

part of the valley. One of these tributaries is called the East Fork of Little Bear River, and has a total length from its head waters to its mouth in Logan River of 33 miles. The general trend of its course within the mountains is easterly, but after joining the South Fork the

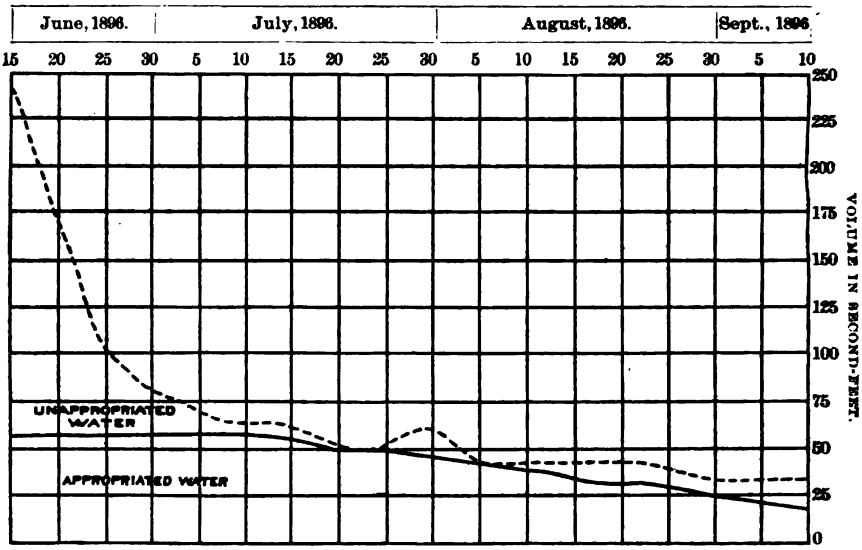

FIG. 6.—Diagram showing appropriated and unappropriated waters of South Fork of Little Bear River.

combined waters flow in a northerly direction to Logan River. The South Fork is fed by numerous springs and rivulets which flow from the south side of the divide lying between Cache Valley and Ogden Valley, and its greatest length from its source to its confluence with the East Fork is 10 miles. The following table gives the names and

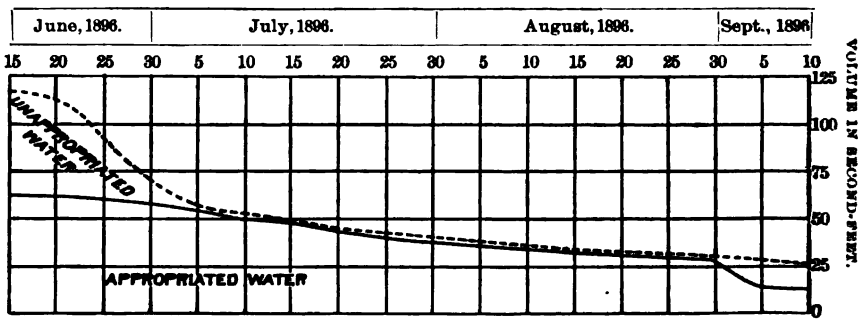

FIG. 7.—Diagram showing appropriated and unappropriated waters of East Fork of Little Bear River.

the capacities at stated periods of each ditch or canal diverting water from Little Bear River and its tributaries. A glance at figs. 6 and 7 shows that the waters of both forks were nearly all utilized during the past season.

In this portion of the valley the gain due to seepage waters fr irrigated areas and from the adjacent bench lands is of considera value to the inhabitants of Wellsville. On July 15, 1896, the flow the South Fork was 61 second-feet. On the same date Hyr Canal was diverting 55 second-feet, and a surplus of 24 second-f remained in the river. These figures show a gain from seepage a deep-seated springs of 43 second-feet. Subsequently the sprin were measured and aggregated nearly 20 second-feet, thus leaving balance of 23 second-feet of seepage waters.

Irrigating canals diverting water from Little Bear River.

Name of canal or ditch.	June.		July.		August.		September.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
From East Fork.								
Jackson Surplus Ditch	19	3	10	2.3	6	Dry.	----	----------
Frank Law Ditch	19	1.6	10	Dry.	----	----------	----	----------
Facer Ditch	19	6.8	10	1.1	6	Dry.	----	----------
Paradise Irrigation and Reservoir Company's Canal	19	50.2	10	47.2	6	35.1	15	22.5
From South Fork.								
Nichols Ditch	----	----------	11	Dry.	----	----------	----	----------
Davis & Co.'s Ditch	----	----------	11	Dry.	----	----------	----	----------
Hyrum Canal	----	----------	11	57.4	6	40.1	15	12.8
From main stream.								
South Field Ditch	----	----------	11	2.7	6	Dry.	----	----------
Paradise Hollow Ditch	----	----------	14	2.5	7	2	15	Dry.
Miller Ditch	----	----------	14	2.8	7	1.4	15	Dry.
Wellsville East Field Ditch	----	----------	14	26.1	7	4.9	12	2.6

CUB RIVER.

Cub River, the main source of supply for the northern portion o Cache Valley, rises in Idaho, flows in a southwesterly direction for distance of 28 miles, and empties into Bear River. The six ditche which head on this stream were each measured three times last sum mer, with results as stated in the following table. The highest is th Cub River and Worm Creek Irrigation Company's canal, which sup plies with water the town of Preston, Idaho. It is taken out on th north side of the river, and conveyed through a pass in the ridg into Worm Creek channel, which is used to convey the canal wate to a lower elevation, where it is again diverted into several ditche that distribute irrigating water to the various precincts of Preston The next canal of any considerable importance is that of the Cu River and Middle Ditch Irrigation Company, which on June 2 carried 50.7 second-feet. By far the largest canal on this strean

was begun in 1860, for the purpose of watering bench lands located north of Franklin, on the right bank of Cub River. Owing, however, to a grave error in the grade, the project was temporarily abandoned, and it was not until after the settlement of Lewiston that a resurvey was made and the canal completed. It is now known as the Lewiston Ditch, or canal. The lowest canal, but the first to divert water from Cub River, if one excepts the Perkins Ditch, which is now practically abandoned, is the Franklin City Ditch, which was built in 1864 by Messrs. Parkinson, Smart, Woodward, and others.

The accompanying diagram (fig. 8) showing the appropriated and unappropriated waters of Cub River, indicates a large surplus during the months of June, but after July 10 the flow is nearly all utilized by the various canals.

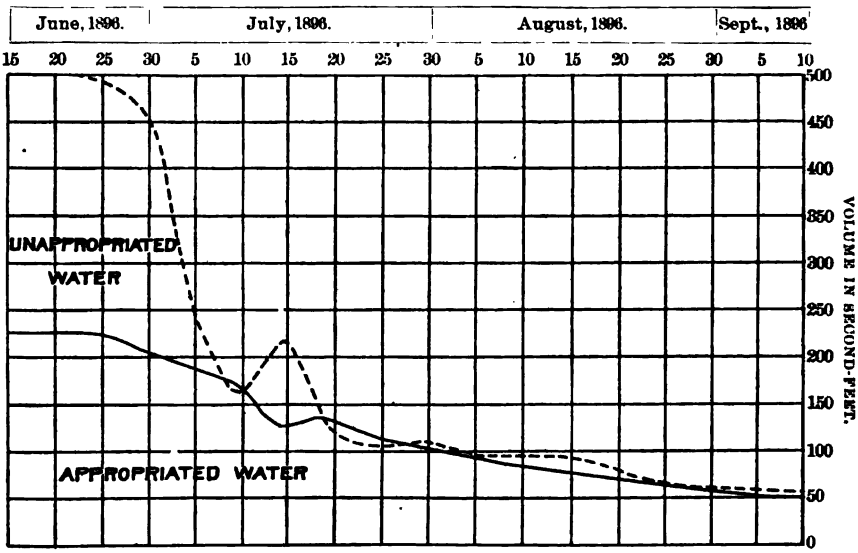

FIG. 8.—Diagram showing appropriated and unappropriated waters of Cub River.

Irrigating canals diverting water from Cub River in Oneida County, Idaho.

Name of canal or ditch.	June.		July.		August.		September.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
Cub River and Worm Creek Irrigation Company's canal	25	42.5	27	31.8	....	.....	7	8.4
Morehead, Taylor, and Kent Ditch	25	4.8	26	1.5	....	.....	7	Dry.
Cub River and Middle Ditch Irrigation Company's canal	25	50.7	27	15.9	....	.....	7	12.0
Taylor ditch	25	Dry.	27	2.1	....	.....	7	Dry.
Lewiston ditch	25	122.1	27	51.0	....	.....	7	30.2
Franklin City ditch	26	5.6	28	2.4	....	.....	7	Dry.

HIGH CREEK.

High Creek is a tributary of Cub River. It rises near the boundary line between Utah and Idaho and flows in a southwest course for a distance of about 9 miles. Numerous ditches, as may be seen by the following table, take water from this comparatively small stream, but, with the exception of the two Richmond canals, their discharges during July and August are small. The Richmond Irrigation Canal, increased by a portion of the flow from Cherry Creek, waters the sloping bench lands lying between High Creek and Richmond. This canal, when augmented by the flow from City Creek, also furnishes water for the upper portion of the town of Richmond. The lower portion of this town and the farm lands adjacent thereto are watered by the Richmond City Canal.

Irrigating canals diverting water from High Creek, in Cache County, Utah.

Name of canal or ditch.	June.		July.		August.		September.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
Williams and Derney Ditch	28	1.3	29	Dry.				
Upper High Bair Ditch	28	2.9	29	Dry.				
Upper Coveville Ditch	28	7.8	29	Dry.				
Richmond Irrigation Company's Canal	28	43.2	29	2.5			9	1.0
Williams Bros., Eckelson and Day Ditch	28	3.6	29	Dry				
Norman Day Ditch	28	0.7	29	Dry.				
Richmond City or Irrigation Canal	28	25.5	29	16.4			9	3.8
Two Eleventh Ditch	28	8.7	29	0.9			9	1.0
Lower Coveville Ditch	28	6.8	29	1.2			9	2.1
J. Bright Ditch	28	8.9	29	2.8			9	0.6

SUMMIT CREEK.

Summit Creek has its source near the head waters of Logan River, and after flowing in a southwesterly course for a distance of 13 miles empties into Bear River. The summer flow of this creek is diverted through various canals, a list of which is given in the order of elevation in the following table, and is used to irrigate the town lots of Smithfield and the farm lands adjacent thereto. A portion of the flow is first used for mechanical purposes, but is subsequently diverted for irrigation purposes.

Irrigating canals diverting water from Summit and Birch creeks in Cache County, Utah.

Name of canal or ditch.	June.		July.		August.		September.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
Roskelly Ditch			3	Dry.				
Peterson Ditch			3	Dry.				
Surplus Ditch			3 31	13.0 3.9			10	2.8
Union Milling Company's Ditch			3 31	3.6 1.1			10	0.8
Mack's Old Mill Race Ditch			3 31	14.1 5.0			10	3.1
City Ditch			3 31	1.0 0.3			10	0.2
Morehead Ditch			3 31	0.7 0.2			10	0.1
Levy Ditch			3 31	11.9 3.6			10	1.6
Big Ditch			3 31	21.8 6.7			10	4.8

MISCELLANEOUS MEASUREMENTS.

The following table gives the results of measurements made of the flow of canals and ditches from other streams within Cache Valley other than those before described:

Results of measurements of irrigation canals and ditches.

Name of canal or ditch.	June.		July.		August.		September.	
	Date.	Dis charge in sec. ft.	Date.	Dis-charge in sec. ft.	Date.	Dis-charge in sec. ft.	Date.	Dis-charge in sec. ft.
From Clarkston Creek.								
Birch Creek ditch					12	3.6	3	3.0
Upper Dam ditch					12	1.9	3	1.4
Lower Dam ditch					12	1.5	3	2.0
From Sugar Creek, Oneida County, Idaho.								
Upper Wheeler ditch			27	0.2			7	Dry.
Taylor and Perkins ditch			27	0.9			7	0.4
Lower Wheeler ditch			27	0.9			7	Dry.
From Cherry Creek, in Cache County, Utah.								
Upper Cherry ditch	30	10.7	30	6.2			9	1.1
Cherry Creek Water Section canal	30	7.5	30	0.9			9	1.0
From Maple Creek and tributaries, Crooked Creek and Deep Canyon, in Oneida County, Idaho.								
Crooked Canyon Creek ditch	27	0.3	28	0.4			8	Dry.
J. Chatterton and J. Lowe ditch	27	2.7	28	Dry.				
J. Lowe ditch	27	0.4	28	1.0			8	Dry.
Silver Point ditch	26	2.7	28	Dry.				
Maple Creek or Franklin City ditch	26	11.6	28	5.0			8	3.1
Stalker and Woodward ditch	27	1.7	28	2.9			9	0.6
Woodward ditch	26	3.5	28	Dry.				
Stalker and Flack ditch	26	4.6	28	1.7			8	Dry.
From Spring Creek, at Providence, in Cache County, Utah.								
Bullock ditch			8	0.7	3	1.3	14	0.4
Bear ditch			8	2.2	3	3.9	14	Dry.
South Bench ditch			8	10.6	3	11.7	14	4.2
Upper ditch			8	9.5	3	3.5	14	6.8
Town ditch			8	6.7	3	3.4	14	2.9
Accommodation ditch			8	0.9	3	Dry.	14	0.2
From Weston Creek, in Oneida County, Idaho.								
Lapray and Norton and Coburn ditches			18	2.6	11	1.4	4	0.8
No. 1 ditch			18	3.6	11	1.5	3	1.6
Georgson ditch			18	2.3	11	1.8	3	1.4
Weston Town ditch			18	2.4	11	1.4	3	2.1
East ditch			17	2.5	11	1.0	4	1.0
South Field ditch			17	4.3	11	3.9	4	3.0

Smaller creeks and springs of Cache Valley from which water is diverted for irrigating purposes.

Name.	June.		July.		August.		September.		October.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
City Creek (Richmond)			1	2.6	1	Dry.				
City Creek (Clarkston)			17	0.9	12	0.8	3	0.7		
Deep Canyon Creek (Mendon)			16	1.4	12	1.5	11	1.2		
Dry Canyon Creek (Avon)					5	0.8	15	Dry.		
Dry Creek (Weston)			18	0.5			15	Dry.		
Flat Canyon Creek	27	0.9	28	Dry.						
Green Canyon Creek	13	5.9	31	Dry.						
Hyrum Dry Canyon Creek					6	0.4	15	Dry.		
Millville Creek			9	3.9	4	4.3	14	4.5		
Myler Creek			17	0.3	12	0.4	3	0.4		
New Canyon Creek			15	4.5	8	4.9	12	4.5		
Nebo Creek			1	0.6	30	Dry.				
Ox Killer Creek	27	0.4	28	Dry.						
Pole Canyon Creek					6	1.5				
Spring Creek (Richmond)	30	1.3	29	0.3			9	Dry.		
Three Mile Creek					12	0.1	11	Dry.		
Twin Creek			16	1.1	13	1.6	11	1.2		
Worm Creek	24	1.7	26	Dry.						
Coburn Spring							4	0.6		
Clayton Spring			15	1.8	8	1.9	12	1.6		
Done et al. springs									22	10.2
Gardner Spring			15	5.0	8	4.3	12	3.5		
Gibson et al. springs									22	6.5
Gitten Spring			16	0.4	13	0.5	12	0.4		
Garr Spring			9	3.6	5	3.2	14	3.1		
Graveyard Spring			16	0.6	13	0.5	11	0.4		
Hyrum Field Seepage springs					7	10.2				
Halverson Spring			30	0.5						
J. Stone and T. Lowe Spring	27	1.5					8	0.2		
Millville Creamery Spring							7	3.6		
Marks et al. springs									22	3.8
Michelson Spring							3	0.3		
Merrill et al. springs									22	5.8
New Dam Spring			15	4.0	8	4.3				
North Field Dam Spring No. 1			15	7.0	8	7.5				
North Field Dam Spring No. 2			15	4.0	8	3.6				
Pond Spring (Mendon)			16	1.1	12	0.9	11	1.1		
Pond Spring (Logan)							11	7.5		
Rocky Point Spring			16	1.6	12	0.5	11	0.3		
Wellsville City Spring			15	3.0						
Wm. Cunningham's Spring							12	0.15		
Wm. Hugh's Spring	26	0.17								
Newton Reservoir			17	8.6	12	4.9	2	1.9		
Hopkins's Slough									23	6.5

Sources of water supply in Cache Valley not used in irrigation in Cache County.

Name of source.	June.		July.		August.		September.		October.	
	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.	Date.	Discharge in sec. ft.
Bear River at Battle Creek	23	3,954.1	25	1,187.2			5	872.6		
Do			25	1,198.8			28	820.7		
Do			25	1,197.9						
Spring Creek (Mendon)									20	66.4
Spring Creek (Millville)									27	4.4
Spring Creek (Franklin)									23	1.4

RESULTS OF STREAM MEASUREMENTS.

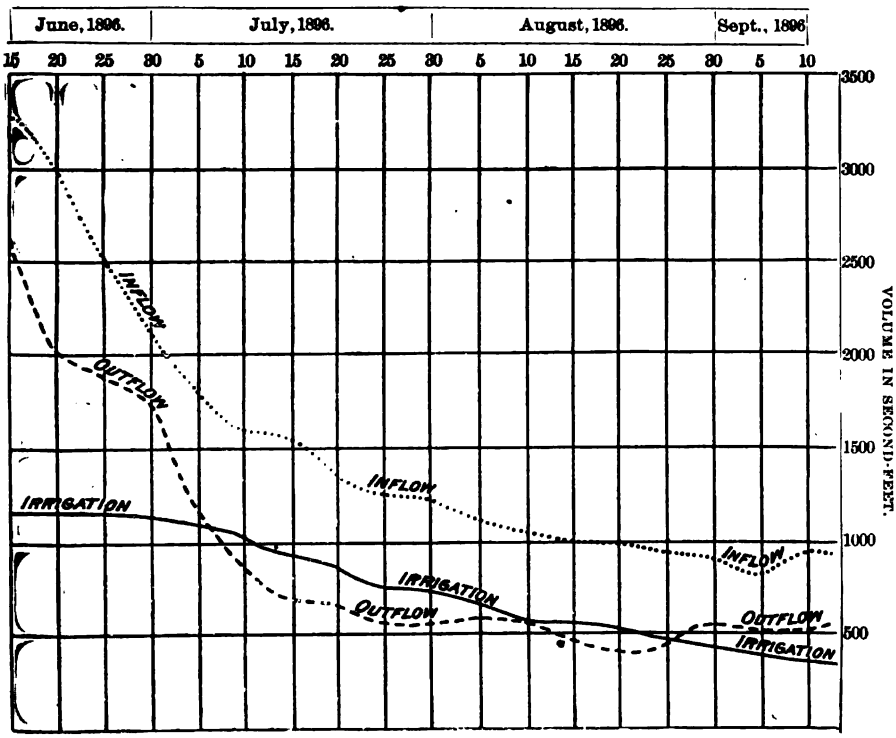

FIG. 9.—Diagram of water supply of Cache Valley, exclusive of Bear River.

For purposes of comparison some of the results of the stream and canal measurements made in Cache Valley during the summer of 1896 are summarized in the diagrams of figs. 9 and 10. Fig. 9 shows the inflow, outflow, and irrigating waters of the valley exclusive of Bear River, while fig. 10 includes both the inflow and outflow of Bear River. As has been stated, no water is diverted from this river in Cache Valley, all the water now utilized being obtained from the various

tributaries. The aggregate discharge of all these tributaries, including wells and springs, is shown by the curved line termed "inflow" in fig. 9. This diagram also shows the total amount of the inflow which was used for irrigation purposes and the surplus which was discharged into Bear River.

It will be seen that the volume used for irrigation on any one day does not represent the difference between the inflow and the outflow on the same day. On every day from June 15 to September 15, 1896,

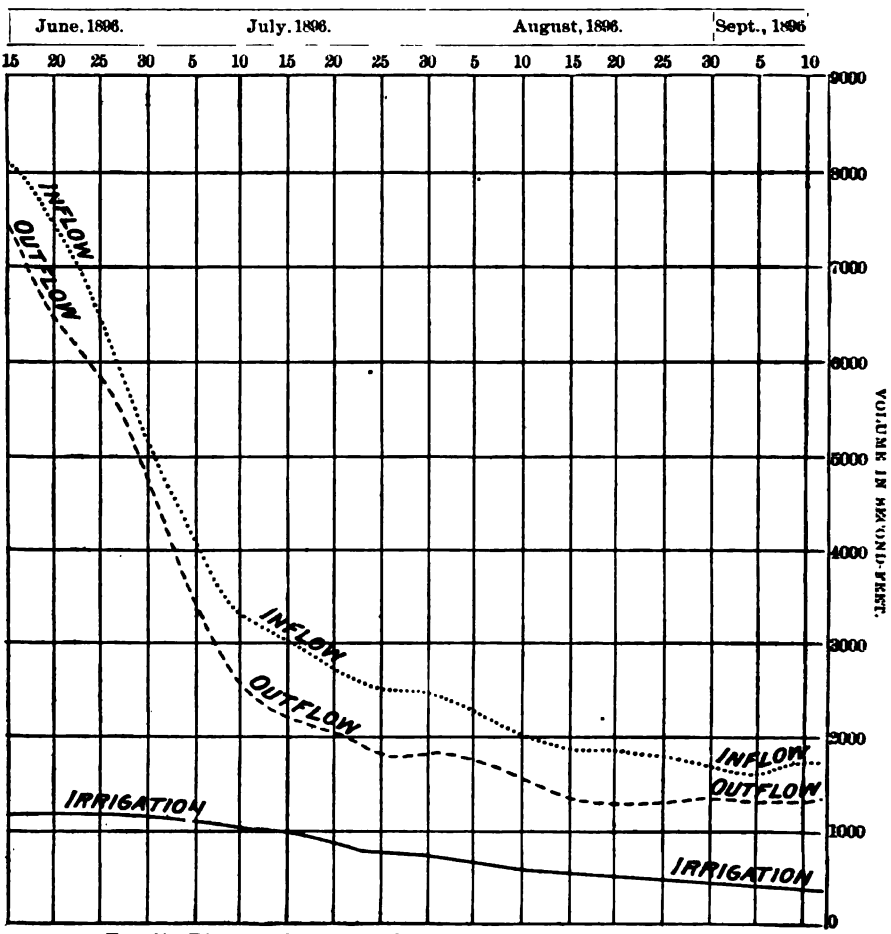

FIG. 10.—Diagram of water supply of Cache Valley, inclusive of Bear River.

excepting a few days in August, there was a gain due to seepage waters. This gain during the latter half of June averaged a continuous flow of 500 second-feet, or 18 per cent of the inflow, but it decreased rapidly until the 20th of August, when it began to increase gradually to September 15. In the following table are given, in cubic feet per second, the volume flowing into the valley, Bear River excepted,

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the volume diverted for irrigation, and the outflow, besides the average monthly gain, resulting from seepage waters.

Water supply of Cache Valley, exclusive of Bear River, in second-feet.

Date.	Inflow.	Irrigation.	Outflow	Average monthly gain from seepage.
1896.				
June 15	3,275.8	1,163.1	2,659	
June 20	3,006	1,162.9	2,029	
June 25	2,537.5	1,159 1	1,884	500.4
June 30	2,107.6	1,136	1,739	
July 5	1,805.9	1,081.9	1,149	
July 10	1,571.4	1,020.2	849	
July 15	1,552.5	925.5	684	181.6
July 20	1,341.3	860	674	
July 25	1,244.2	755.6	554	
July 30	1,224 4	731 9	554	
August 5	1,108.2	632.2	557	
August 10	1,036.9	573.4	562	
August 15	998.6	547 5	462	34
August 20	997.7	512.3	417	
August 25	938.4	470.5	438	
August 30	905.2	442.8	553	
September 5	813.2	394.7	508	
September 10	938.9	352.7	508	61.5
September 15	864.6	334.7	603	

The rainfall from June 15 to September 15 on the 450 square miles lying within the area bounded by the locations of the stream measurements in Cache Valley was 3.58 inches, or an equivalent of 85,920 acre-feet of water. Assuming, for the present, that the amount of water evaporated from the surface of the irrigated area, together with that transpired by the leaves of cultivated plants, would aggregate a depth of 12 inches during the three months from June 15 to September 15, the loss due to evaporation over an irrigated area of 38,625 acres would equal 38,625 acre-feet. Again, if we assume that the water evaporated from the surface of the uncultivated portions of the valley was 4 inches during the same time, this loss over an area of 450 square miles, less 38,625 acres, or 249,375 acres, would equal 83,125 acre-feet. Comparing the losses due to evaporation with the gain from rainfall, the former is the greater by 35,830 acre-feet, which would maintain a stream of 200 second-feet for nearly three months.

If we assume that the rainfall just balances the evaporation, then the gain due to seepage would be so given in the above table. In this case the amount evaporated from the surface of the uncultivated portion of the valley in three months would be less than 2¼ inches, an amount apparently too small.

Irrigating duty of water in Cache Valley in 1896.

Month.	Duty of water in acres per sec. ft.
1896.	
June	52
July	67
August	113
September	166
Average	99.5

The figures given above include all the waste arising from absorption, seepage, and evaporation in the conveyance of the water as well as all waste caused by imperfect methods of irrigating.

FIG. 11.—Bear River at Collinston Utah.

SEEPAGE WATERS IN OGDEN VALLEY.

This valley comprises the highest irrigated land in Weber County. It is separated from Great Salt Lake Valley by a narrow spur of the Wasatch Mountains and is watered by the South, Middle, and North forks of Ogden River and several small creeks. The three main tributaries meet near the lower part of the valley and form Ogden River,

which traverses the mountain range through a c
long, having an average fall in that distance of
The torrential character of the river in this port
fig. 12. All of the water flowing from the uppe
through this narrow gorge.

The irrigators of Ogden Valley supply annual
water diverted from Ogden River and its tributari
small map, Pl. III. This diversion is, however, il

FIG. 12.—Narrows of Ogden River.

of scarcity, since all the summer flow belongs to
whose canals are situated in the lower portions
relative location being shown on the left half of
putes have arisen between the irrigators of the t
prevent costly litigation, the writer sought to det
whether water could be diverted and applied to th
valley without lessening materially the supply t
below.

The results of measurements made in 1894 are given in the following table:

Ogden Valley inflow and outflow in 1894.

Date.	Inflow, in second-feet.	Volume used in irrigation.	Outflow, in second-feet.	Seepage waters and private springs.
July 10	154.0	140.0	156.5	142.5
15	129.8	121.0	140.7	131.9
20	127.2	104.7	119.2	96.7
25	118.6	93.5	105.4	80.3
30	107.1	85.0	106.8	84.7
Aug. 5	96.0	77.5	99.7	81.2
10	88.5	74.0	106.8	92.3
15	81.2	71.4	100.5	90.7
20	76.5	66.0	106.8	96.3
25	75.0	56.5	110.4	91.9
30	73.1	44.0	113.0	83.9
Sept. 5	80.2	31.0	121.2	72.0
10	79.0	27.0	119.2	67.2

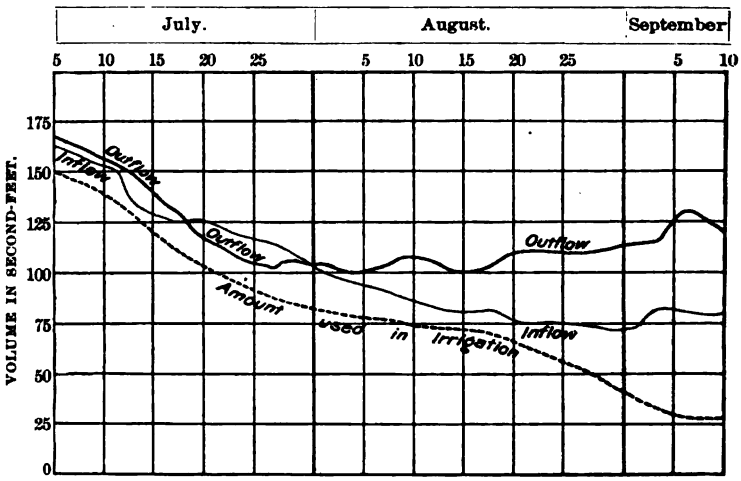
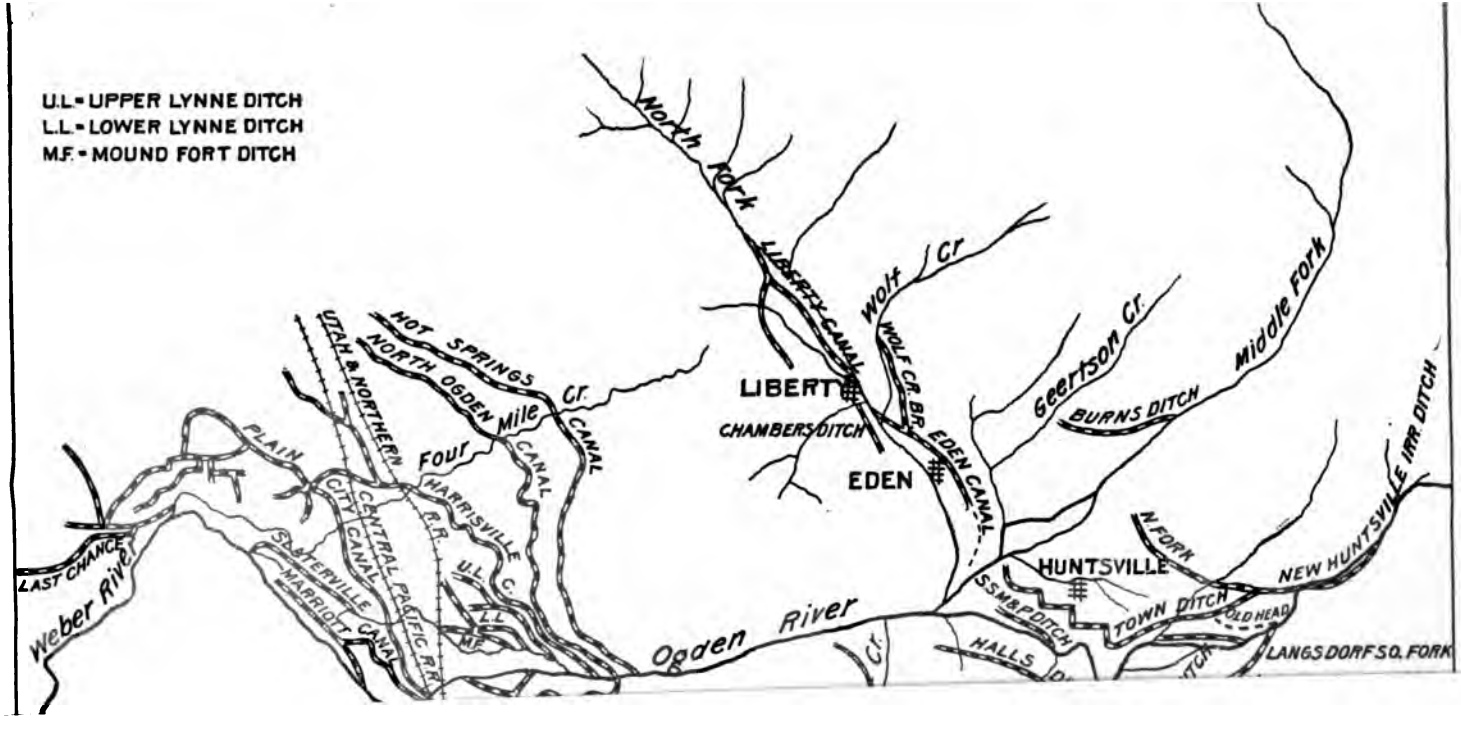


FIG. 13.—Diagram illustrating inflow and outflow of Ogden Valley.

A more detailed description of the measurements is to be found in a preliminary report on seepage water and the underflow of rivers,[1] published in 1895. The general facts are illustrated by the accompanying diagram, fig. 13, illustrating the inflow and outflow of Ogden

[1] Utah Agricultural Experiment Station Bulletin No. 38, by Samuel Fortier, hydraulic engineer, February, 1895.


U.L.= UPPER LYNNE DITCH
L.L.= LOWER LYNNE DITCH
M.F.= MOUND FORT DITCH
North Fork
LIBERTY CANAL
Wolf Cr
WOLF CR. BR.
EDEN CANAL
LIBERTY
CHAMBERS DITCH
EDEN
Geertson Cr.
Middle Fork
BURNS DITCH
NEW HUNTSVILLE IRR. DITCH
N. FORK
HUNTSVILLE
TOWN DITCH
OLD HEAD
LANGSDORF S.O. FORK
SSM&P DITCH
HALLS
Ogden River
HOT SPRINGS
NORTH OGDEN
Mile
Four
Cr.
CANAL
HARRISVILLE
UTAH & NORTHERN
CENTRAL PACIFIC R.R.
R.R.
U.L.
L.L.
M.F.
PLAIN
CITY CANAL
SHOTTERVILLE CANAL
MARRIOTT
LAST CHANCE
Weber River

Valley, and by the dotted line the amount used in irrigation. If no water returned by seepage or was added by percolation from the adjacent mountain lands, the outflow would be represented by the vertical distance between the dotted line representing the amount used in irrigation and the light line representing the inflow; but, as shown by the heavy line, the actual outflow is far greater than this, being larger at times than the inflow upon the corresponding dates.[1]

To be more certain that the ratio existing between the inflow and outflow of this valley was correctly determined in 1894, the writer sent Messrs. Rhead and Humphreys with a different current meter to make a similar test during 1896. The results obtained by them, given below, corroborate the records of 1894:

Results of measurements in Ogden Valley in 1896.

Date—1896.	Inflow in second-feet.	Volume used in irrigation.	Outflow in second-feet.	Seepage waters and private springs.
Aug. 20	91.6	106.5	101.1	116.0
25	86.0	99.2	99.5	112.7
30	78.7	89.4	97.4	108.1
Sept. 5	70.0	79.2	95.0	104.2
10	62.8	70.2	93.0	100.4
15	55.3	60.7	90.0	95.4
20	50.4	51.6	89.1	90.7

Some of the Ogden Valley canals, such as the Eden Canal, obtain a portion of their discharge from seepage waters, and this accounts for the fact that the aggregate volume used in irrigation exceeds the inflow.

[1] The public lands and their water supply, by F. H. Newell: Sixteenth Ann. Rept. U. S. Geol. Survey, Part II, 1895, p. 529.

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Sixteenth Annual Report of the United States Geol
Papers of an economic character, 1895, octavo,

Contains a paper on the public lands and their water
by a large map showing the relative extent and locatio
report on the water resources of a portion of the Great

A geological reconnoissance of northwestern Wyor
1894, octavo, 72 pp. Bulletin No. 119 of the Un
price, 10 cents.

Contains a description of the geologic structure of p
Big Horn Basin, especially with reference to the coal f
supply and agricultural possibilities.

Report of progress of the division of hydrography
by F. H. Newell, 1895, octavo, 176 pp. Bulletin
Geological Survey; price, 15 cents.

Contains results of stream measurements at various po
and records of wells in a number of counties in wester
eastern Colorado.

1896.

Seventeenth Annual Report of the United States Ge
II, Economic geology and hydrography, 1896, oc

Contains papers by G. K. Gilbert on the undergroun
eastern Colorado; by Frank Leverett on the water reso
ton on a reconnoissance of the artesian areas of a portio

Artesian-well prospects in the Atlantic Coastal Pl
1896. octavo, 230 pp., 19 plates. Bulletin No. 138
ical Survey; price, 20 cents.

Gives a description of the geologic conditions of the
N. Y., to Georgia, and contains data relating to many of

Report of progress of the division of hydrography f
F. H. Newell, hydrographer in charge, 1896, octa
of the United States Geological Survey; price, 2

Contains a description of the instruments and method
and the results of hydrographic investigations in variou

1897.

Eighteenth Annual Report of the United States Geol
IV, Hydrography, 1897, octavo, — pp. (In prep

Contains a progress report of stream measurements for
and four other papers relating to hydrography. The fir
and relates to the water resources of Ohio and Indiana, es
next is by N. H. Darton, on the artesian waters of South
his paper in the Seventeenth Annual; following this is a
D. Schuyler, on water storage, mainly for irrigation and
paper, by Robert T. Hill, describes the artesian conditi
vicinity of San Antonio.

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2. Irrigation near Phoenix, Arizona, by Arthur P. Davis, 1897.
3. Sewage irrigation, by George W. Rafter, 1897.
4. A reconnoissance in southeastern Washington, by Israel C. Russell, 1897.
5. Irrigation practice on the Great Plains, by E. B. Cowgill, 1897.
6. Underground waters of southwestern Kansas, by Erasmus Haworth, 1897.
7. Seepage waters of northern Utah, by Samuel Fortier.
8. Windmills for irrigation, by E. C. Murphy.
9. Irrigation near Greeley, Colorado, by David Boyd.
10. Irrigation in Mesilla Valley, New Mexico, by F. C. Barker.
11. River heights for 1896, by Arthur P. Davis.
12. Water resources of southeastern Nebraska, by Nelson Horatio Darton.

In addition to the above, there are in various stages of preparation other papers relating to the measurement of streams, the storage of water, the amount available from underground sources, the efficiency of windmills, the cost of pumping, and other details relating to the methods of utilizing the water resources of the country. Provision has been made for printing these by the following clause in the sundry civil act making appropriations for the year 1896-97:

Provided, That hereafter the reports of the Geological Survey in relation to the gauging of streams and to the methods of utilizing the water resources may be printed in octavo form, not to exceed 100 pages in length and 5,000 copies in number; 1,000 copies of which shall be for the official use of the Geological Survey, 1,500 copies shall be delivered to the Senate, and 2,500 copies shall be delivered to the House of Representatives, for distribution. (Approved, June 11, 1896; Stat. L., vol. 29, p. 453.)

The maximum number of copies available for the use of the Geological Survey is 1,000. This quantity falls far short of the demand, so that it is impossible to supply all requests. Attempts are made to send these pamphlets to persons who have rendered assistance in their preparation through replies to schedules or donation of data. Requests specifying a certain paper and stating a reason for asking for it are attended to whenever practicable, but it is impossible to comply with general demands, such as to have all of the series sent indiscriminately.

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DEPARTMENT OF THE INTERIOR

WATER-SUPPLY

AND

IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 8

WINDMILLS FOR IRRIGATION.—MURPHY

WASHINGTON
GOVERNMENT PRINTING OFFICE
1897

IRRIGATION REPORTS.

The following list contains the titles and brief descriptions of the principal reports relating to water supply and irrigation prepared by the United States Geological Survey since 1890:

1890.

First Annual Report of the United States Irrigation Survey, 1890, octavo, 123 pp.

Printed as Part II, Irrigation, of the Tenth Annual Report of the United States Geological Survey, 1888–89. Contains a statement of the origin of the Irrigation Survey, a preliminary report on the organization and prosecution of the survey of the arid lands for purposes of irrigation, and report of work done during 1890.

1891.

Second Annual Report of the United States Irrigation Survey, 1891, octavo, 395 pp.

Published as Part II, Irrigation, of the Eleventh Annual Report of the United States Geological Survey, 1889–90. Contains a description of the hydrography of the arid region and of the engineering operations carried on by the Irrigation Survey during 1890; also the statement of the Director of the Survey to the House Committee on Irrigation, and other papers, including a bibliography of irrigation literature. Illustrated by 29 plates and 4 figures.

Third Annual Report of the United States Irrigation Survey, 1891, octavo, 576 pp.

Printed as Part II of the Twelfth Annual Report of the United States Geological Survey, 1890–91. Contains a report upon the location and survey of reservoir sites during the fiscal year ending June 30, 1891, by A. H. Thompson; "Hydrography of the arid regions," by F. H. Newell; "Irrigation in India," by Herbert M. Wilson. Illustrated by 93 plates and 190 figures.

Bulletins of the Eleventh Census of the United States upon irrigation, prepared by F. H. Newell, quarto.

No. 35, Irrigation in Arizona; No. 60, Irrigation in New Mexico; No. 85, Irrigation in Utah; No. 107, Irrigation in Wyoming; No. 156, Irrigation in Montana; No. 157, Irrigation in Idaho; No. 163, Irrigation in Nevada; No. 178, Irrigation in Oregon; No. 193, Artesian wells for irrigation; No. 198, Irrigation in Washington.

1892.

Irrigation of western United States, by F. H. Newell; extra census bulletin No. 23, September 9, 1892, quarto, 22 pp.

Contains tabulations showing the total number, average size, etc., of irrigated holdings, the total area and average size of irrigated farms in the subhumid regions, the percentage of number of farms irrigated, character of crops, value of irrigated lands, the average cost of irrigation, the investment and profits, together with a résumé of the water supply and a description of irrigation by artesian wells. Illustrated by colored maps showing the location and relative extent of the irrigated areas.

1893.

Thirteenth Annual Report of the United States Geological Survey, 1891–92, Part III, Irrigation, 1893, octavo, 486 pp.

Consists of three papers: "Water supply for irrigation," by F. H. Newell; "American engineering and engineering results of the Irrigation Survey," by Herbert M. Wilson; "Construction of topographic maps and selection and survey of reservoir sites," by A. H. Thompson. Illustrated by 77 plates and 119 figures.

A geological reconnoissance in central Washington, by Israel Cook Russell, 1893, octavo, 108 pp., 15 plates. Bulletin No. 108 of the United States Geological Survey; price, 15 cents.

Contains a description of the examination of the geologic structure in and adjacent to the drainage basin of Yakima River and the great plains of the Columbia to the east of this area, with special reference to the occurrence of artesian waters.

1894.

Report on agriculture by irrigation in the western part of the United States at the Eleventh Census, 1890, by F. H. Newell, 1894, quarto, 283 pp.

Consists of a general description of the condition of irrigation in the United States, the area irrigated, cost of works, their value and profits; also describes the water supply, the value of water, of artesian wells, reservoirs, and other details; then takes up each State and Territory in order, giving a general description of the condition of agriculture by irrigation, and discusses the physical condition and local peculiarities in each county.

Fourteenth Annual Report of the United States Geological Survey, 1892–93, in two parts, Part II, Accompanying papers, 1894, octavo, 597 pp.

Contains papers on "Potable waters of the eastern United States," by W J McGee; "Natural mineral waters of the United States," by A. C. Peale; "Results of stream measurements," by F. H. Newell. Illustrated by maps and diagrams.

(Continued on third page of cover.)

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, April 13, 1897.

SIR: I have the honor to transmit herewith a manuscript entitled Windmills for Irrigation, by E. C. Murphy, professor of civil engineering in the University of Kansas, at Lawrence. This gives the results of experimental tests carried on during the summer of 1896 upon windmills located for the greater part in the vicinity of Garden, Kansas. These results are presented in condensed form for early publication in order that they may be available for use and discussion by persons interested in the matter. They should be considered as preliminary to a more popular presentation, which, however, can be given only when a considerable number of experimental measurements of various kinds have been completed and a careful study yielding general conclusions has been made.

In detailed work of this character it is impossible to avoid technical discussions and mathematical formulas, but as far as possible the results of the tests have been expressed in graphic diagrams. A careful study and comparison of these and of the accompanying descriptions shows the difference of behavior of the mills examined under the conditions in which they were found. It is, of course, impossible to draw conclusions applicable to all mills from the examination of a few, but the facts here shown are significant and worthy of careful consideration.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

WINDMILLS FOR IRRIGATION.

By E. C. Murphy.

INTRODUCTION.

The windmill has long been employed to perform mechanical work. Just when and where the first windmill was used is not definitely known, but we know that a considerable number were utilized in France in the twelfth century. They were employed in Holland in the fifteenth century in pumping surface water over the dikes into the sea. It is not the purpose of this paper, however, to trace the history[1] or development of windmills, but to present the results of some recent measurements on the useful work windmills are doing, especially when employed to pump water. It is surprising to note how little definite information there is in regard to the efficiency of windmills, especially of the steel back-geared mills of the present day. Thousands, perhaps hundreds of thousands, are in use doing work of various kinds, and yet very few careful measurements have been made to determine their horsepower or the number of foot-pounds of work they are accomplishing under different velocities. It was to supply in a measure this lack that in 1895 the writer undertook to measure, with instruments then at his disposal, the pumping power of windmills. In 1896, with much better facilities, he continued this work, extending it to include power as well as pumping mills. The attempt was not made to measure the power of every make of mill; that was impossible. It was thought best to confine the work to different sizes of the standard mills, those that are used to a large extent and are giving satisfaction. In some cases two or three tests of the same size and make of mill were made for the purpose of showing the influence of the pump or well on the useful work done.

Perhaps nowhere in the United States is irrigation from wells by the use of windmills so extensively practiced as in the vicinity of Garden. Here are found hundreds of windmill pumping plants, irrigating from 1 to 15 acres, the pumps lifting from 3 to 14½ quarts per stroke to a height of from 10 to 45 feet. Here are found the large steel mills, with the latest improvements, running day and night whenever

[1] The Windmill as a Prime Motor, by Alfred R. Wolff, 1890, chapter 3, contains an account of the early history of windmills.

the wind velocity is sufficiently great. These reasons induced the writer to select this locality as the field of his investigations.

WELLS NEAR GARDEN, KANSAS.

A brief description of the water supply and the wells of this locality may assist in conveying an understanding of what follows. The water is found in sand and gravel at distances below the surface varying from 8 to 40 feet. This material is in layers of variable thickness and different degrees of coarseness, ranging from fine sand to large gravel. It is overlain by a layer of sandy clay, which in some places will stand vertical for years without any support. In other places there is very little clay in this layer. The wells are usually 3 to 4 feet square, and cased with wood through the top sandy clay to the water-bearing sand; then a wood or galvanized-iron casing from 12 inches to 3 feet in diameter extends down from 8 to 20 feet into the sand to a layer of gravel. Where this latter casing is large, three or more galvanized-iron pipes 6 to 12 inches in diameter are put down in the bottom of it, and these sometimes have wire gauze over their tops to keep down the sand. These galvanized-iron pipes have perforations about one-fourth inch in diameter for a distance of 2 feet or more from the bottom for letting in the water. In many cases instead of this small open well the supply pipe is on a well point whose diameter is the same as that of the supply pipe, and whose length varies with the diameter. These well points have not given satisfaction, and are being replaced by the open well.

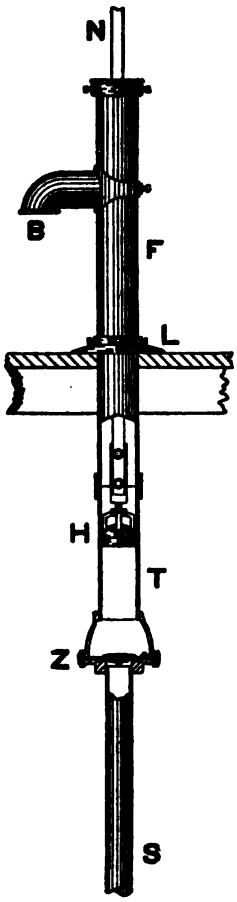


FIG. 1.—View of Gause pump.

N, plunger; B, spout; F, discharge pipe; L, flange for platform; H, plunger; T, cylinder; Z, enlarged valve opening and check valve; S, suction pipe.

The difficulty with many of the wells is that they are not large enough; the water in them is lowered too rapidly, producing such a rapid inflow as to carry sand, which cuts the valves and cylinder lining.

PUMPS.

Nearly all the pumps in use in this vicinity with windmills are of the reciprocating-piston type. Fig. 6 shows what is called the Stone pump, manufactured by R. G. Stone, of Garden. They are made in three sizes—6-inch, 8-inch, and 10-inch, these dimensions being the approximate diameter of the discharge pipe. The

diameter of the cylinder is less than this by twice the thickness of the brass lining. The valves shown in fig. 7 are of the latest form;

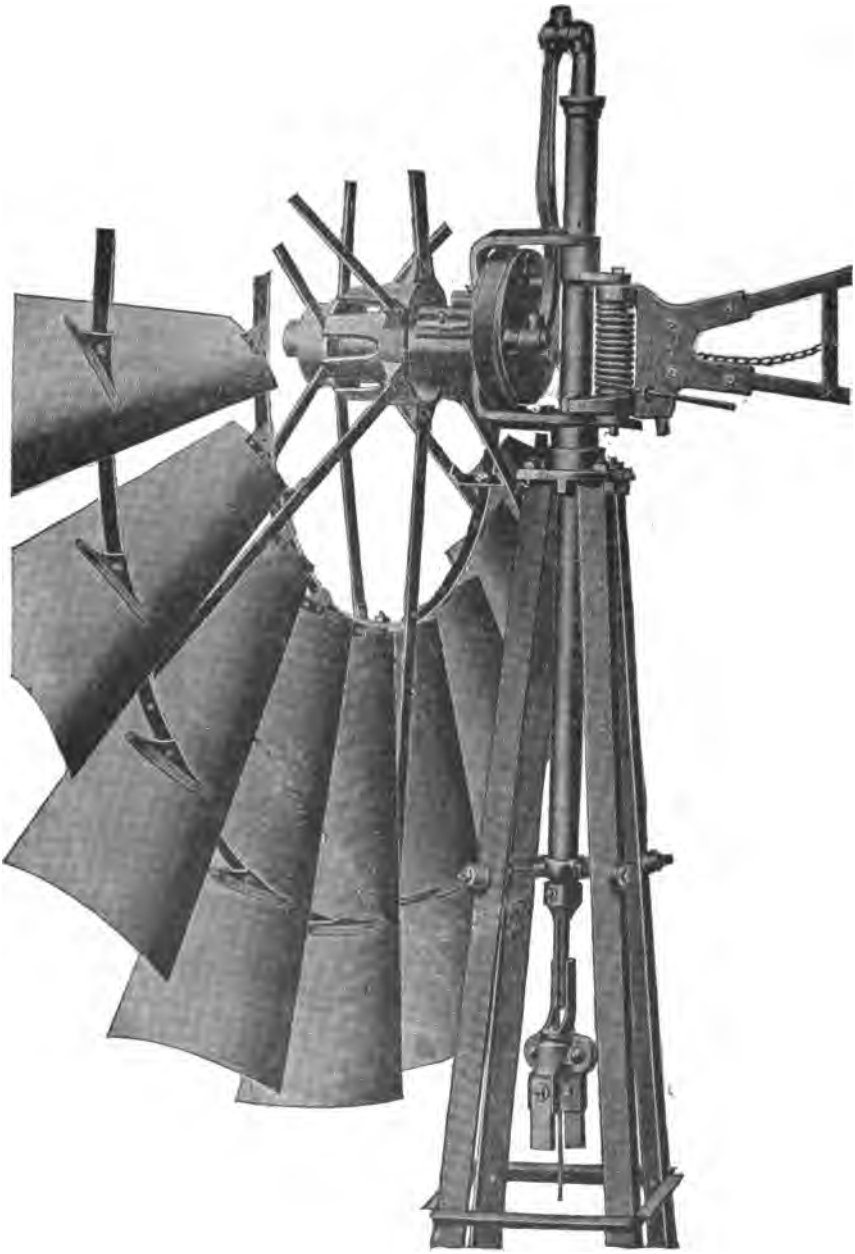


FIG. 2.—Working parts of Woodmanse Mogul.

the plunger valve is of the single-flap or clack form, and the check of the disk form, made so the water can pass up in the center as well

as around the sides. In an earlier form of this pump the plunger valve is of the double-flap or butterfly form, and the check of the lift form, but having no opening at the center. Probably nine-tenths of all the pumps in use near Garden are of the Stone variety. Fig. 1 shows the Gause pump, one of the first used there for irrigating purposes. It is more expensive than the Stone, and is not so much used now. Fig. 14 shows cylinder of 8-inch Frizell pump, a few of which are in use. Fig. 4 shows the Woodmanse pump, which is used with windmill No. 2. Fig. 24 shows a crude home-made pump called the "water-elevator." One of these is in use in Garden.

FIG. 3.—Sectional view of Woodmanse pump.

INSTRUMENTS AND METHODS.

The wind velocity was measured with a United States Weather Bureau cup anemometer. Each mile of wind was recorded electrically by one pen of a two-pen register. By means of a little device fastened to the pump an electric circuit is closed at each stroke of the pump and a record made by a recorder. Another electric circuit leading from the recorder to the other pen of the register is closed at each hundred strokes of the pump, and a record made on the register; hence the graphic record of the register shows the number of miles of wind in any given time, and also the number of hundred strokes of pump in the same time.

The anemometer was held on a pole at the height of the axis of the

wheel of the windmill. The pole was made so that its length could be increased at will from 25 to 50 feet. The anemometer on the pole is shown in Pls. I and VIII.

The discharge per stroke of the pump was found by catching the water for several strokes in a tub and measuring this with a quart measure. This was found to vary with the number of strokes per minute in a few cases on account of the valves leaking. The discharge given where it varied is for nearly a maximum speed of pump. The lift or distance from the surface of water in the well to the center of the water column as it leaves the discharge pipe was measured when the pump was working quite rapidly. For pump on well points it was estimated from the depth to water when the point was put down, making an allowance for the pumping down of the water.

In the following pages descriptions are given of each of the mills tested, these being illustrated by a few photographs of the mills and surroundings and by drawings of the common form of pumps employed. The descriptions are also accompanied by diagrams showing graphically the results obtained by the measurement of the velocity of the wind and by counting the number of strokes of the pump. These diagrams exhibit at a glance the facts which otherwise can be comprehended only by a careful study and analysis of the figures. As the wind increases from a gentle breeze the pumps run faster, the number of strokes per mile of wind increasing rapidly up to a certain point, but beyond this point the diagrams show that although the wind increases in speed, the pump begins to run slower. This apparent eccentricity is due to the simple fact that nearly all mills are so constructed that for safety they begin to turn out of the wind when it reaches a certain force, and thus decrease their revolutions, until in a heavy wind the movement becomes quite slow or may even cease altogether, the vanes being as a rule turned edgewise to the direction of the air currents.

In these diagrams (figs. 4, 8, 9, 10, 11, 13, 15, 16, 18, and 20) the relation between the movement of the wind in miles per hour and the number of strokes of the pump is shown by the curved line. The space from left to right on these diagrams is proportional to the velocity of the wind, while the distance from the lower line upward is proportional to the number of strokes of the pump. The data expressed by these diagrams were obtained directly from the record given by the anemometer register. The pen of this connected with the anemometer makes, we will assume, 3 short marks (3 miles) in 15 minutes, indicating a mile in 5 minutes, or at a rate of 12 miles an hour. At the same time the other pen, connected with the pump and registering each hundred strokes, makes, say, 2 short marks, showing that the pump has made 200 strokes for this 3 miles of wind movement, or 67 strokes in each mile. This fact is entered upon the diagram by placing a small circle at a distance from the right corresponding to 12

miles per hour and a distance from the bottom corresponding to 67 strokes. In this way each observation is indicated. When these points have been plotted, the smooth curve is sketched so as to occupy an intermediate position among these. In order to determine the number of strokes more accurately than was done by the automatic recorder, these were actually counted for a considerable number of the observations.

DESCRIPTION OF MILLS TESTED.

Mill No. 1.—The tests on this mill were preliminary or experimental toward the perfection of the instruments employed, and were not completed for discussion.

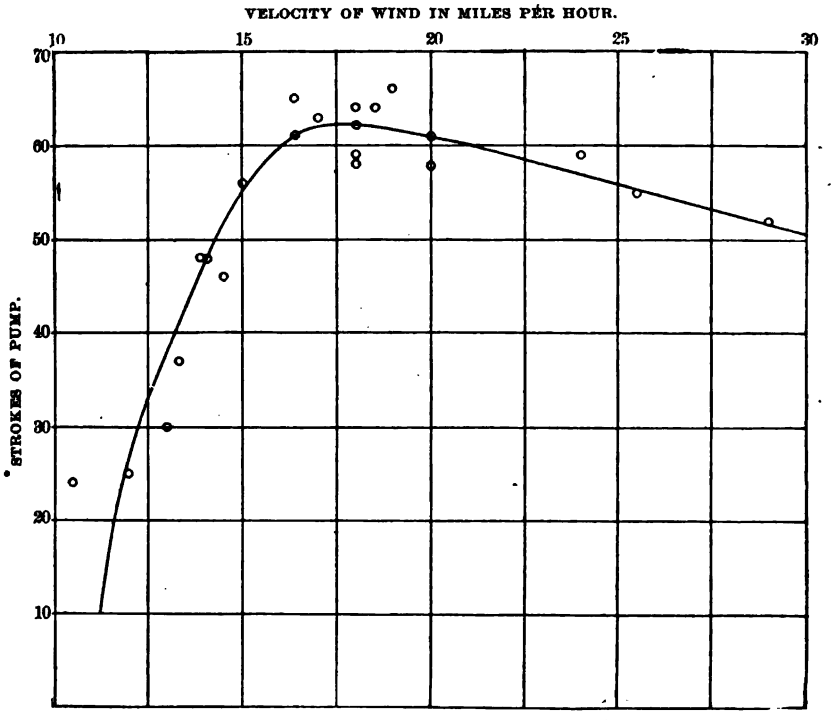


FIG. 4.—Diagram showing results with mill No. 2.

Mill No. 2.—This is a 12-foot Woodmanse Mogul, manufactured by Woodmanse-Hewitt Manufacturing Company, Freeport, Illinois. Pl. I shows the mill, tower, pump, and pond, and fig. 2 the working parts. The tower is steel, 50 feet high to the axis of the wheel. The wind exposure is not good from the north, the mill being 115 feet south of a large barn. The wheel has 30 curved fans, each 36 by 13 by 5½ inches, set at an angle of 30° with the plane of the wheel. It is back geared 3 to 1 and held in the wind by a spring. The pump is Woodmanse make, shown in fig. 3. The cylinder is 9½ inches in diameter; the supply pipe is 5⅝ inches in diameter; the length of stroke is 12

VIEW OF MILL NO. 2, WOODMANSE, AND ANEMOMETER.

inches. The well is $3\frac{3}{4}$ by $3\frac{3}{4}$ feet to water, a distance of 14 feet. In the bottom of this is put down a 12-inch galvanized iron pipe 20 feet into water, forming a small open well. The lift at the time of test was $17\frac{3}{4}$ feet and the discharge per stroke $14\frac{1}{2}$ quarts. The mean barometer pressure was 26.98 inches, and the mean temperature 94°. The cost of mill, tower, pump, and well was about $210. The curve,

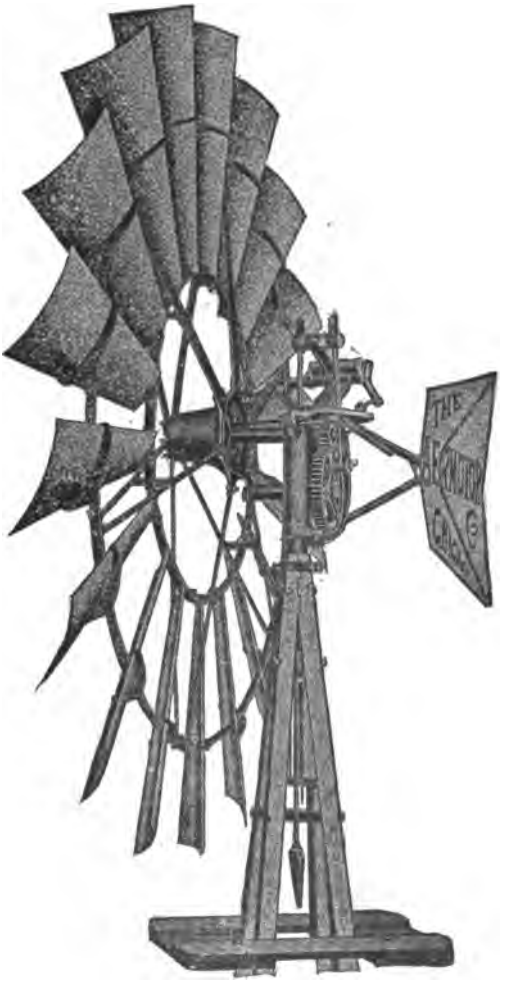


FIG. 5.—Working parts of aermotor.

FIG. 6.—Stone pump.

shown in fig. 4, is for a moderately loaded 12-foot mill (536.2 foot-pounds per stroke), and is seen to start with a wind velocity of about 11 miles per hour. It ascends very rapidly, reaching a maximum at 18 miles per hour, and giving 60 strokes per mile. The rest of the curve to 30 miles has a gentle slope; the number of strokes per minute, from about 5 at 12 miles to about 25 at 30 miles per hour.

Mill No. 8.—This is a 12-foot aermotor, manufactured by the Aermotor Company, Chicago, Illinois. Pl. II shows the mill with its tower, pump, and pond, and fig. 5 the working parts. This mill had been in use about a year and all the parts were in good working order. The tower is made of wood, having the axis of the wheel 30 feet above the ground. The exposure is very good. The wheel has 18 curved fans, each 44 by 18¾ by 7¾ inches, set at an angle of 31° to the plane of the wheel. It is back geared 3⅓ to 1, and is held in the wind by a spring. The pump is the Stone make (figs 6 and 7), in which the check valve is of the single-flap variety, and the plunger valve the double-flap variety. The cylinder is 9½ inches in diameter; the

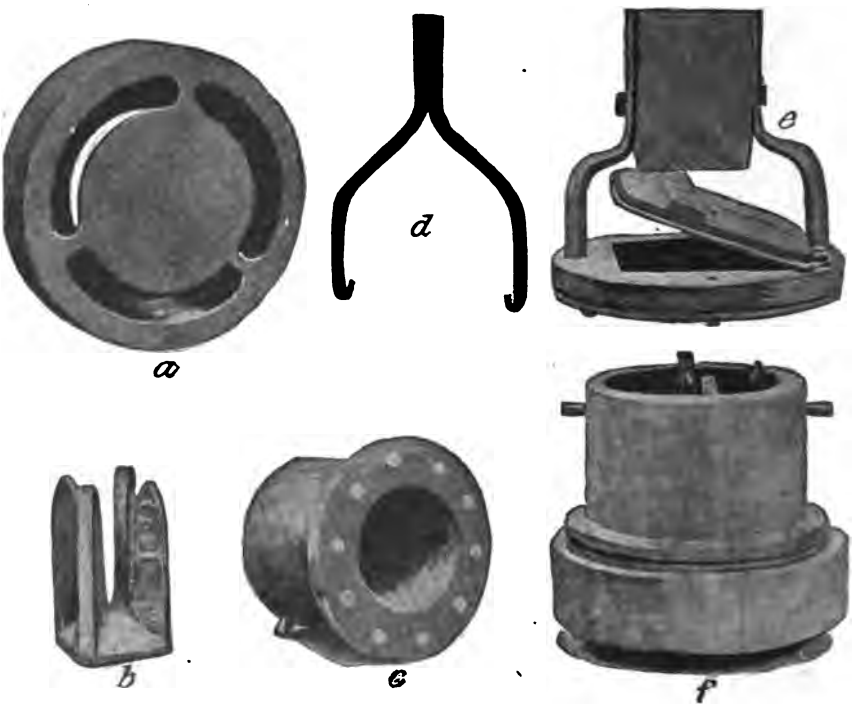
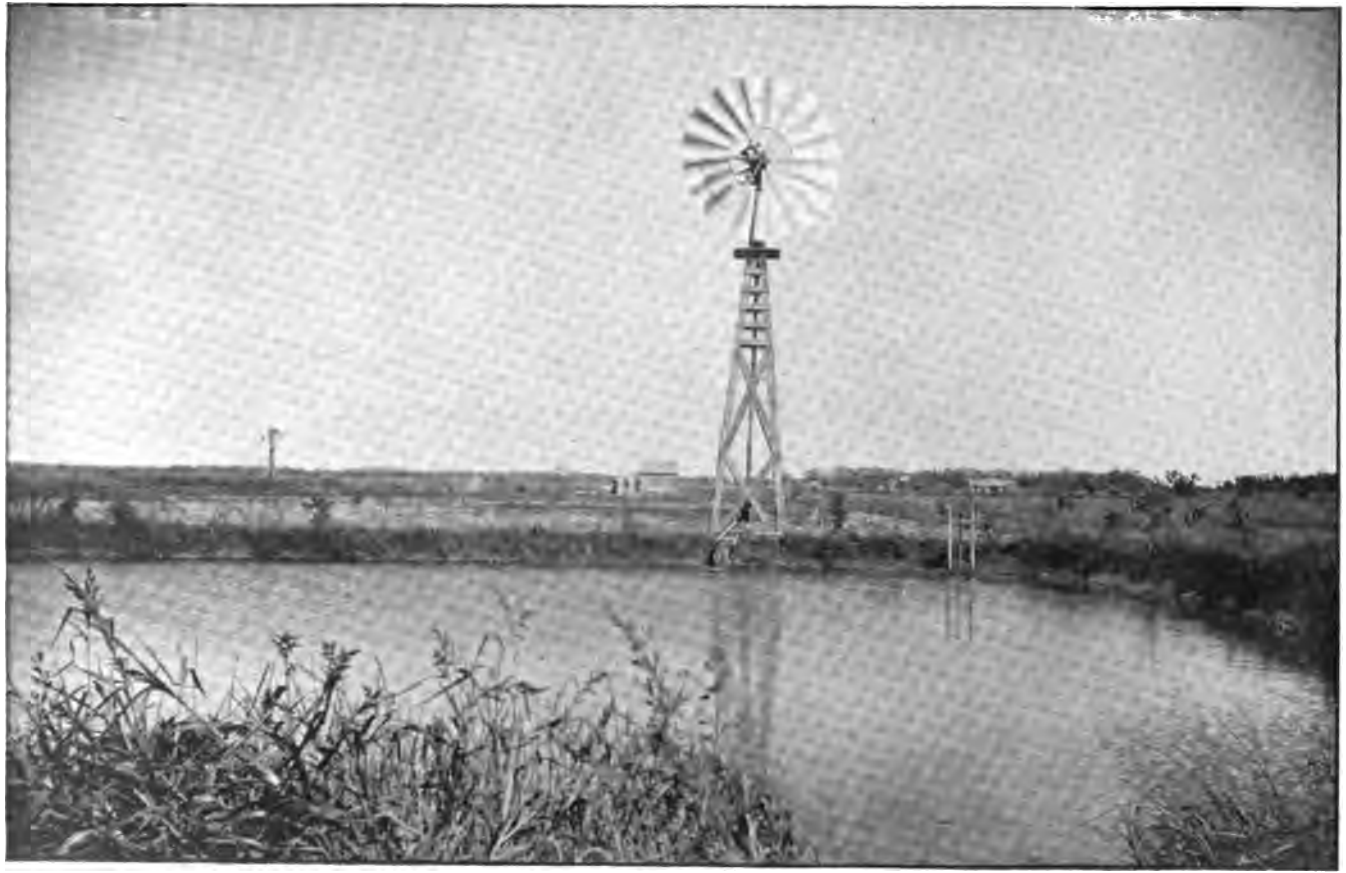


FIG. 7.—Valves of Stone pump. *a*, lower valve-seat; *b*, ring guide to lower valve; *c*, lower or check valve; *d*, hook for removing lower valve; *e*, plunger and valve; *f*=*a*, *b*, and *c* combined.

supply pipe is 4 inches in diameter, and the discharge pipe is 10 inches in outside diameter. The length of stroke is 12 inches and the discharge per stroke 14½ quarts. The well is 4 by 4 feet and is sunk a distance of 8 feet, being down nearly to water. From this to a depth of 18 feet it is 3 feet in diameter. In the bottom of this are three pipes 12 inches in diameter extending down 5 feet farther. The lift at the time of testing was 13¾ feet. The barometer pressure was 27.2 inches, and the temperature 85° F. The water is pumped into a pond 80 by 75 feet, and a depth of 22 inches can be drawn off. The cost of the plant, including mill, tower, pump, and pond, was $145.



VIEW OF MILL NO. 3, AERMOTOR.

The curve shown in fig. 8 is for a rather lightly loaded mill—415.3 foot-pounds per stroke. It starts at a velocity of 6 to 7 miles per hour, ascends less rapidly than in fig. 4, attains a maximum at about 15 miles per hour, when the number of strokes per mile is 62, and then descends slowly, reaching 50 strokes at 30 miles. The number of strokes per minute increases from about 5 at 8 miles to 25 at 30 miles.

Mill No. 4.—This, shown in the foreground of Pl. III, is an 8-foot Ideal windmill, manufactured by the Stover Manufacturing Company, Freeport, Illinois. This mill had been in use about one year and all the parts were in good condition. The tower is of wood; the axis of the wheel is 48 feet above the ground. The wheel has 15 fans, each

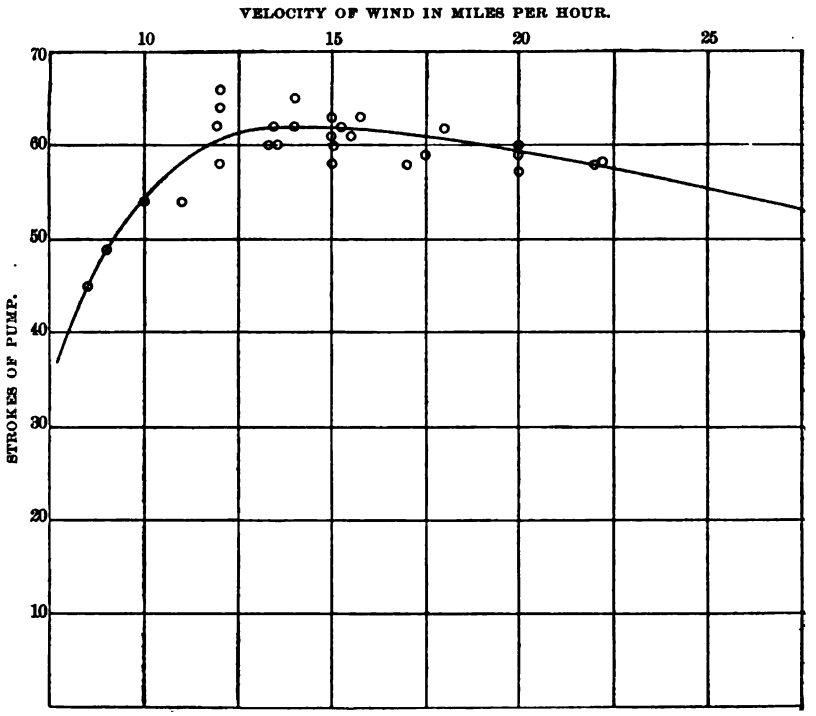


FIG. 8.—Diagram showing results with Mill No. 3.

16⅛ by 7 by 30 inches, set at an angle of 29° with the plane of the wheel. It is back geared 2½ to 1 and is held in the wind by a spring. The pump is of the Stone make. The discharge pipe is 5⅝ inches in diameter and the supply pipe 3 inches in diameter. The length of stroke is 8 inches. The plunger and check valves are of the single-flap variety. The well is 2¾ by 2¾ feet down, nearly to water, a depth of 5¼ feet. The 3-inch supply pipe extends down to a depth of 14 feet, and on the end of it is a 3-inch well point 6 feet long. The lift may vary from 8½ to 20 feet. It was probably about 12 feet at the time of the test. The discharge per stroke was 2 quarts. The mean

barometer pressure was 27.19 inches, and the mean temperature 83° F. The water is pumped into a pond 115 by 31 feet and 3 feet deep. The cost of the plant, including mill, pump, well, and pond, was $80.

The curve shown in Fig. 9, although for a quite lightly loaded 8-foot mill—50 foot-pounds per stroke—is seen to start in a 10 to 11 mile wind. The maximum is reached at 19 miles with a speed of 78 strokes. The right portion of the curve is quite steep and is characteristic of this make of mill. Mill No. 18 is the same size and make as this one, and yet with a load of 89.2 foot-pounds it starts in a 7 to 8 mile wind, reaching a maximum at about 13 miles at a speed of 104 strokes per mile. A second test, when the spring that holds the wind wheel

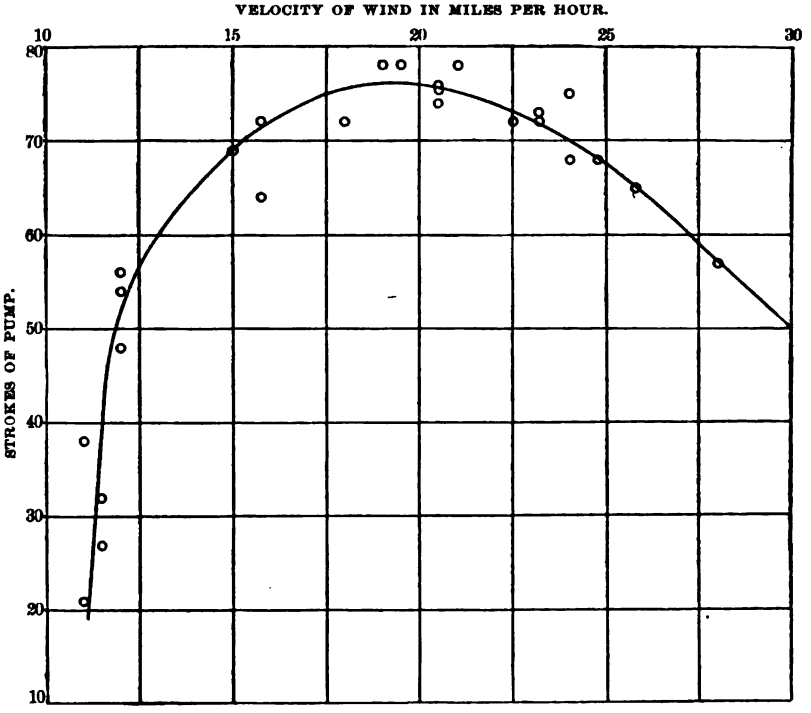


FIG. 9.—Diagram showing results with Mill No. 4.

in the wind was tightened up somewhat, gave the maximum at a velocity of about 15 miles with a pump speed of about 114 strokes. The difference in performance appeared to be due to difference in pumps and wells.

Mill No. 5.—This mill, shown in the background of Pl. III, is an 8-foot aermotor, manufactured by the Aermotor Company, Chicago, Illinois. The tower is of wood and is 28½ feet high to the axis of the wheel. The exposure is good, and all the parts were in good working order at the time of examination, the plant having been in use about one year. The wheel has 18 curved fans, each 30 by 12½ by 5½ inches, making an angle of 29½° with the plane of the wheel. It is

VIEW OF MILL NO. 4, IDEAL, AND NO. 5, AERMOTOR.

back geared 3⅓ to 1. The pump is Stone make. The discharge pipe is 6 inches in diameter; the supply pipe, 3 inches in diameter. The valves are both of the single-flap variety. The length of stroke is 8 inches. The well is 4 by 4 feet to water, a depth of 10½ feet. A 12-inch wooden curb extends 12 feet farther into the sand and gravel. The discharge per stroke was 3½ quarts and the lift 13 feet. The water is pumped into a pond 110 by 30 by 2½ feet. The cost of plant, including pond, was $80.

This 8-foot mill, with a load of 95 foot-pounds, is shown by fig. 11 to start with an 8 to 9 mile wind, reaching a maximum at 13 to 15 miles with 95 strokes per mile. At 30 miles per hour it is making 77

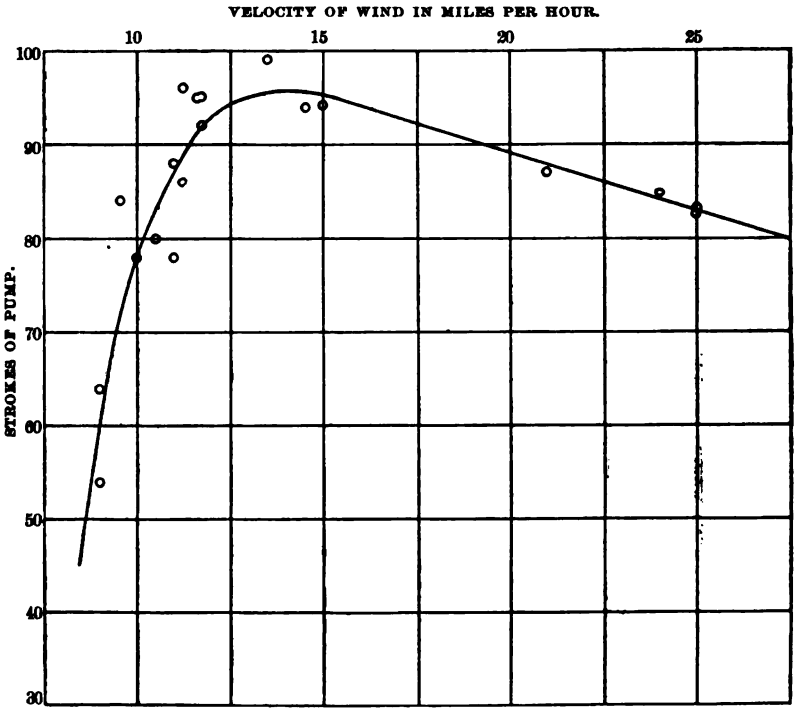


FIG. 10.—Diagram showing results with Mill No. 5.

strokes per mile and 39 per minute. This curve indicates a quite heavily loaded mill.

Mill No. 6.—This mill, shown in the background of Pl. II, is an 8-foot Gem, manufactured by the United States Wind Engine and Pump Company, Kansas City, Missouri. The working parts of the mill are shown in Pl. IV. The exposure is good and all the parts are in good working order, the mill having been in use only about a year. The wheel has 24 curved fans, each 30½ by 10 by 4½ inches, set at an angle of 35° with the plane of the wheel. It is back geared 3 to 1. The wheel is held in the wind by means of a weight. The pump is Stone make. The discharge pipe is 6 inches in diameter, the supply

pipe 4 inches in diameter, and the length of stroke 8 inches. The well is open to water for a depth of 6½ feet. The supply pipe is on a well point, the end of which is 16 feet below the surface of the ground. The lift was 9$\frac{7}{12}$ feet and the discharge 3$\frac{9}{10}$ quarts per stroke. The tower is built of wood and is 24 feet high to the axis of the wheel. The mean barometer pressure was 27.02 inches and the mean temperature 85° F. The plunger valve is of the double-flap variety, and the check of the single-flap variety.

Mill No. 7.—This is a 12-foot aermotor similar to Mill No. 3. The tower is steel, having a height of 31 feet to the axis of the wheel. The exposure was good and all the parts were in good working order, the plant having been in use less than one year. The pump is the Stone make, and is like that with Mill No. 3, except that the check valve is of the solid-lift variety. The lift was 15½ feet, and the discharge 14$\frac{3}{10}$ quarts per stroke. The water is pumped into a pond 135 by 50 by 2½ feet.

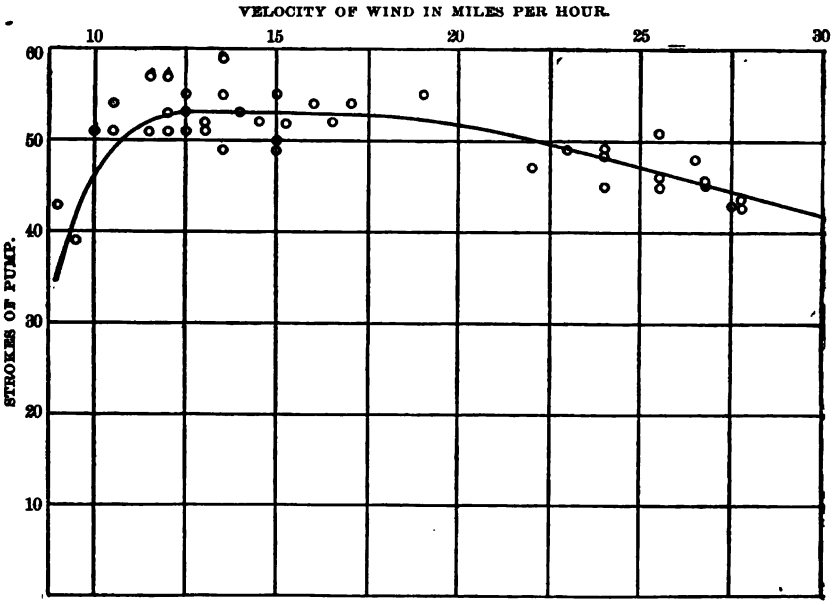
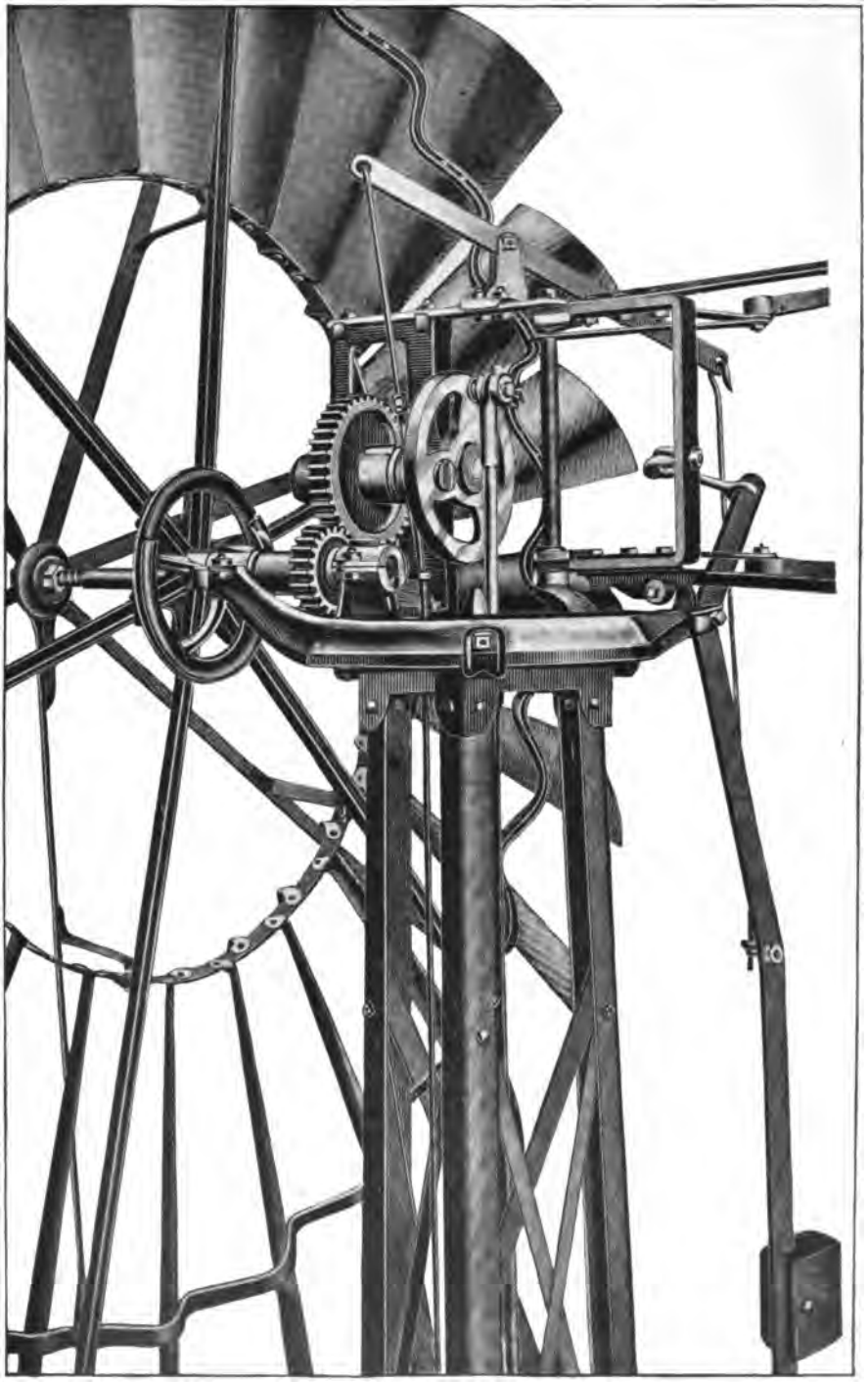


FIG. 11.—Diagram showing results with Mill No. 9, aermotor.

Mill No. 8.—This is a 10-foot Star wooden mill, manufactured by Bradley, Wheeler & Co., Kansas City, Missouri. The tower is made of wood and the axis of the wheel is 35½ feet above the ground. The water is pumped into an elevated tank 20 feet above the surface of the ground, and is used for irrigation. The wheel has 60 plain fans, each 37 by 5 by 2¾ inches, set at an angle of 33° to the plane of wheel. It is held in the wind by means of a weight. It is not back geared, a stroke of the pump being made to each revolution of the wheel. The supply pipe is 2 inches in diameter and terminates in a well point, the end of which is 18 feet below the surface of the ground. The cylinder



WORKING PARTS OF MILL NO. 6, GEM.

is 3 inches in diameter, the discharge pipe 1¼ inches in diameter, the length of stroke 5 inches. The lift may vary between 28½ and 37 feet. It was estimated to be about 30 feet at the time of measurement.

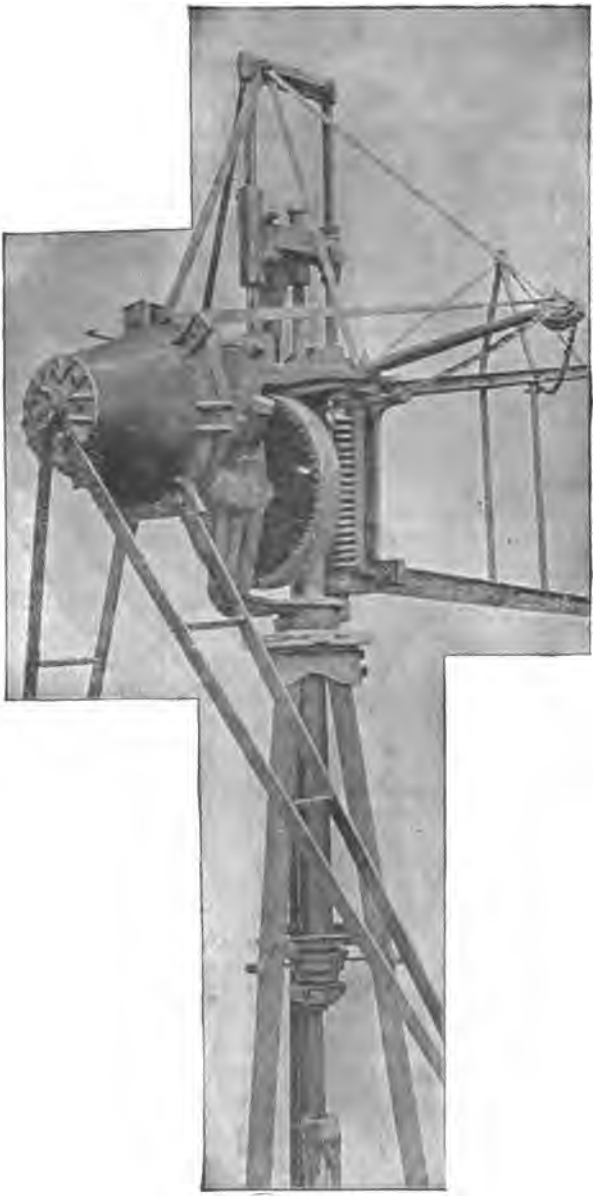


FIG. 12.—Working parts of Mill No. 10, Ideal.

The discharge per stroke was 0.24 quart. The cylinder leaked some at the time of test. After a new cylinder was put in the discharge

per stroke was increased to 0.40 quart. The mean barometer pressure was 27.04 inches; mean temperature, 78° F.

Mill No. 9.—This is a 16-foot aermotor. The tower is steel and the axis of the wheel is 30 feet above the ground. The wheel has 18 curved fans, each 59 by 25¾ by 10½ inches, set at an angle of 30° with the plane of the wheel. It is back geared 3⅓ to 1. The discharge pipe is 12 inches in diameter, the supply pipe 6 inches in diameter, the cylinder 8 inches in diameter; the stroke, 16 inches. The well is 4 by 6 feet to a depth of 23 feet, 2 by 2 feet down 8 feet farther, and 18 inches diameter down 14 feet farther. The water is 39½ feet below the surface of the ground. The lift is 44¼ feet and the discharge 11 quarts per stroke. The check valve is of the single-flap variety and the plunger of the double-flap variety. The mean barometer pressure

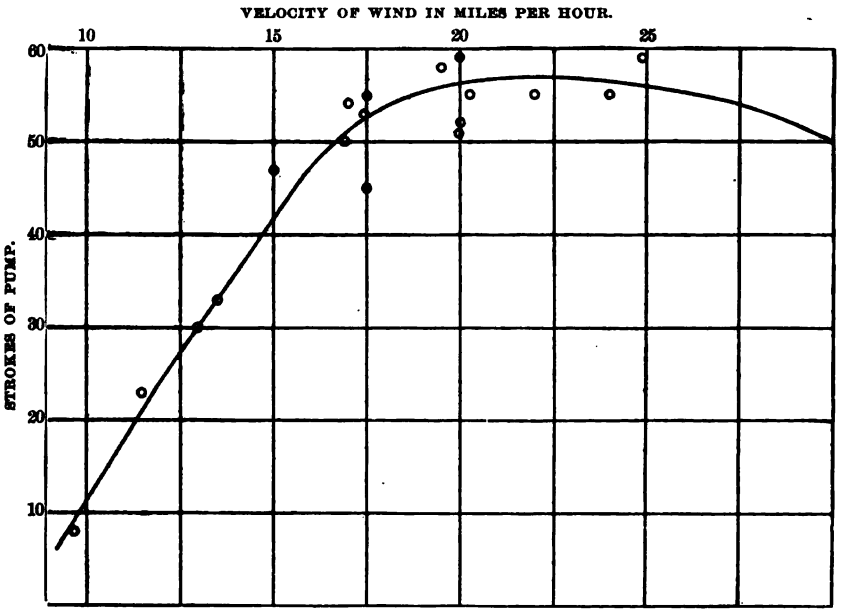


FIG. 13.—Diagram showing results with Mill No. 11, Ideal.

was 27.04 and the mean temperature 93°. This plant has been in use about three years.

The curve, shown in fig. 11, starts with a wind velocity of 8 to 9 miles and reaches a maximum at 13 miles, with a speed of 53 strokes per mile. From this to a velocity of about 19 miles the curve is nearly horizontal. From this point it descends slowly to 32 miles, where it is making 38 strokes per mile. The piston speed increases from the rate of 11 strokes at 12 miles to the rate of 21 strokes at 30 miles per hour.

Mill No. 10.—This is an 8-foot Ideal. The tower is made of wood, the axis of the wheel being 30 feet above the ground. The wheel has 15 curved fans, each 31 by 19 by 7 inches, set at an angle of 29½° with the plane of the wheel. It is back geared 2½ to 1. The supply pipe

is 1½ inches in diameter, the cylinder 2½ inches in diameter. The pump is of the common hand kind, with lift valve of the flap form and plunger of the lift variety. The valves leak some, as the discharge is greater when the pump is working rapidly than when it is working slowly. The supply pipe is on a well point 2 feet long and 1½ inches in diameter, whose lower end is 50 feet below the surface of the ground. The lift was 33 feet and the discharge per stroke one-third of a quart when pumping quite rapidly. The mean barometer pressure was 26.94 inches and the mean temperature 97°.

Mill No. 11.—This is a 12-foot Ideal, the working parts of which are shown in fig. 12. The tower is made of steel, the axis of the wheel being 30 feet above the ground. The exposure is good and all the parts are in good working order. The wheel has 21 curved fans, 31 by 19 by 7 inches, set at an angle of 29½° to the plane of the wheel. It is back geared 2½ to 1, and the wheel is held in the wind by a spring. The discharge pipe is 8 inches in diameter and the stroke 12 inches. The supply pipe consists of two 3-inch pipes 14 feet long, each terminating in a 3-inch well point 3 feet long. The valves are both of the single-flap variety. The water is 39½ feet below the surface of the ground. The lift, as nearly as could be ascertained, was 45 feet at the time of measurement; the discharge, 9 quarts per stroke. The water is pumped into a pond 60 by 40 by 6 feet. This plant has been in use about three years. The mean barometer pressure was 26.91 inches, and the mean temperature 91° F.

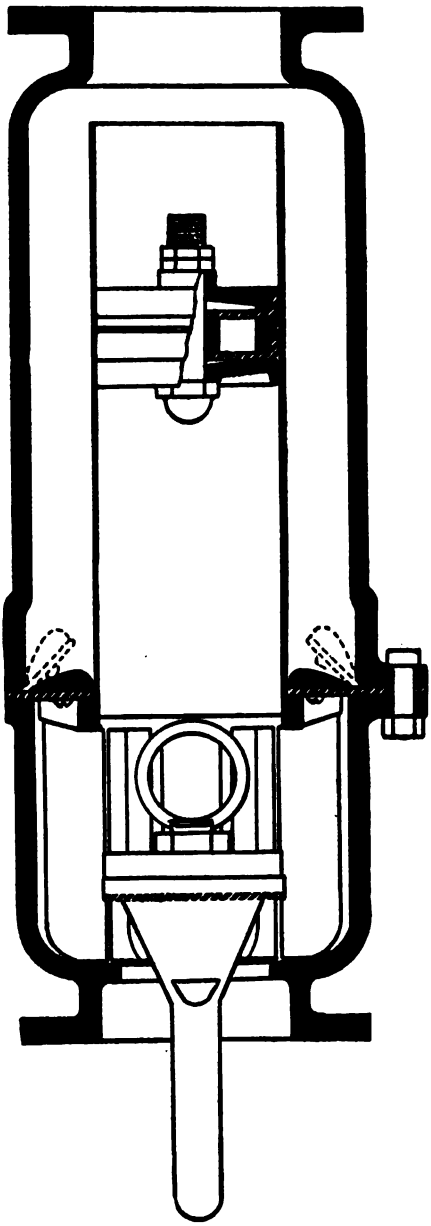


FIG. 14.—Working parts of Frizell cylinder.

This curve, shown in fig. 13, is for a heavily loaded (843.7 foot-pounds per stroke) 12-foot mill. It starts with a velocity of about 10 miles per hour and reaches a maximum at about 23 miles, with a piston speed of 57 strokes per mile. At 30 miles it is making 51 strokes per mile. The maximum point of this curve is much farther to the right than that of any other curve. The number of strokes per minute increases from 5 at 12 miles to 25 at 30 miles.

Mill No. 12.—This is a 14-foot Ideal, shown in fig. 16. The tower is made of steel, 30 feet high to the axis of the wheel. The wheel has 24 curved fans, each 48¾ by 17½ by 8 inches, set at an angle of 30° with the plane of the wheel. It is back geared 2½ to 1. The pump is Frizell make, shown in fig. 14. The discharge pipe is 10 inches in diameter; the cylinder 9½ inches; the supply pipe is 6 inches in diam-

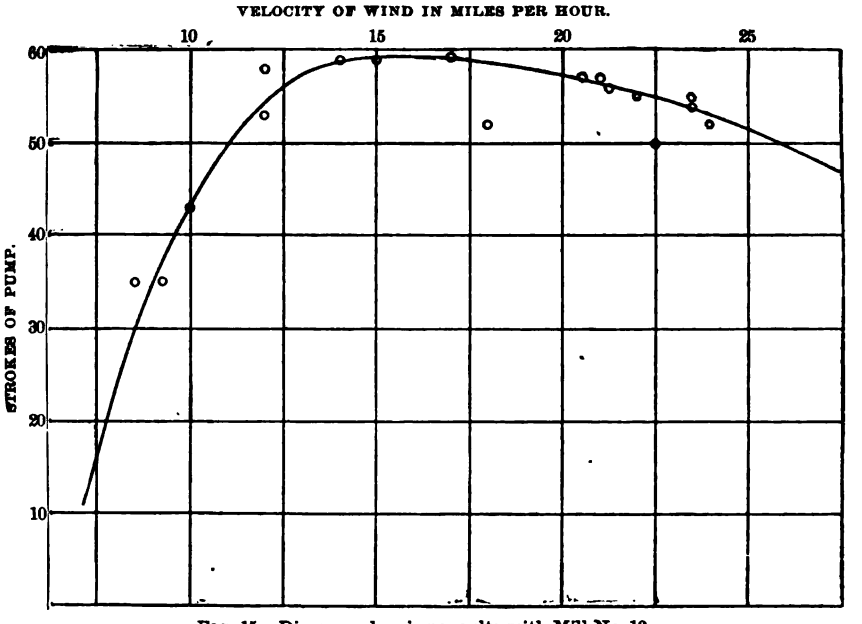
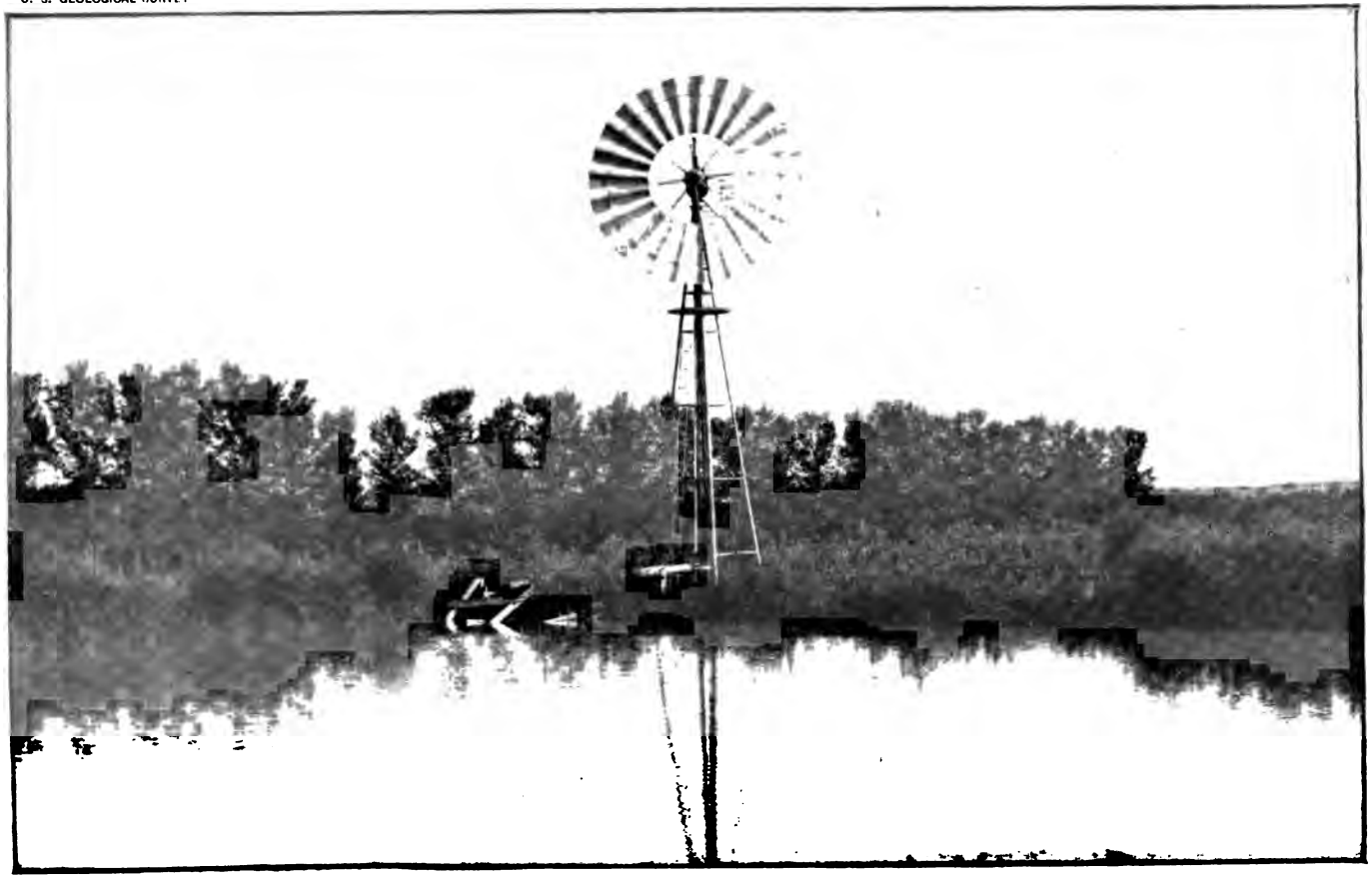


FIG. 15.—Diagram showing results with Mill No. 12.

eter, terminating in a well point 10 feet long and 6 inches in diameter, the lower end of which is 32 feet below the surface of the ground. The lift, as nearly as could be estimated, was 11 feet; the discharge, 11.6 quarts per stroke. The mean barometer pressure was 27.04 inches and the mean temperature 81° F. The water is pumped into a reservoir 100 by 100 feet and 3 feet deep. The pump has been in use about one year.

The curve, shown in fig. 15, is for a very lightly loaded (263.5 foot-pounds) 14-foot mill. This load is only 31 per cent of that of the 12-foot mill, No. 11. The curve starts with a 7 to 8 mile wind and reaches a maximum at 15 miles with a piston speed of 58 strokes per mile of wind. At 30 the piston speed is 47 strokes.



VIEW OF MILL NO. 12, IDEAL.

Mill No. 13.—This is a 12-foot aermotor, shown in Pl. VI. The tower is made of wood, with the axis of the wheel 25 feet above the ground. The exposure is good and the plant in excellent condition, having been in use about one year. The wheel is the same as in mill No. 3. The pump is Stone make; the discharge pipe is 10 inches in diameter; the supply pipe is 5 inches in diameter on a well point 10 feet long, the lower end of which is 17 feet below the surface of the ground. The length of stroke is 12 inches. The plunger valve is of the double-flap type and the check valve of the single-flap variety. The discharge per stroke at the time of the test was 14.4 quarts and the lift about 11 feet. The mean barometer pressure was 27.09 inches and the mean temperature was 91° F. The important difference

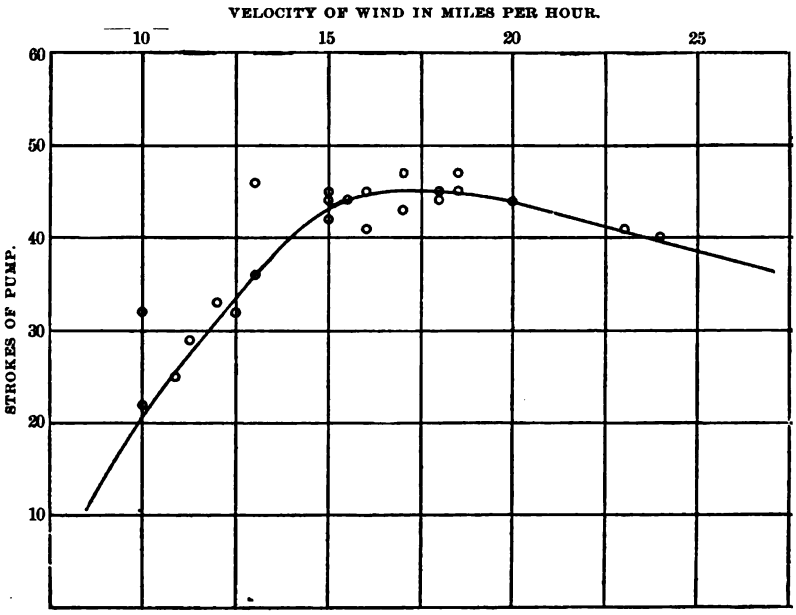


FIG. 16.—Diagram of results with Mill No. 19.

between this plant and No. 3 is that the latter has a 4-inch supply pipe and an open well, while the former has a 5-inch supply pipe on a well point.

Mill No. 14.—This is a 12-foot Gem, like the one shown in Pl. IV, on a 60-foot steel tower. The pump is Gause make; the cylinder is 8 inches in diameter; the length of stroke 9 inches. The supply pipe is a 12-inch open well. The discharge per stroke was 9¾ quarts and the lift 15½ feet. The wind velocity was not measured for this mill.

Mill No. 15.—This is a 10-foot Gem, similar to that shown in Pl. IV. The tower is made of wood, the axis of the wheel being 34 feet above the ground. The mill is in good working order, but the exposure is not good on account of trees. The wheel has 24 fans, each 36 by 11 by 4¾ inches, set at an angle of 35° with the plane of the wheel. It is

back geared 3 to 1. The pump is Stone make; the discharge pipe is 8 inches in diameter, the supply pipe 3 inches in diameter, the stroke 8 inches. The supply pipe is on a 3-inch well point 8 feet long, whose lower end is 21½ feet below the surface of the ground. The plunger valve is of the single-flap form and has a check lift. Depth of water is 10 feet. The discharge per stroke is 7 quarts; the lift, about 15 feet; the mean barometer pressure was 27.05 inches and the mean temperature was 84° F.

Mill No. 16.—This is a 10-foot Halliday, pumping water into the same pond as No. 15. It is similar to the mill shown in fig. 12. The tower is wood, and the axis of the wheel 28 feet above ground. The wheel has 78 fans, each 36¼ by 4 by 2¼ inches, set at an angle of 35½° to the plane of the wheel. It is not back geared. The pump is Gause

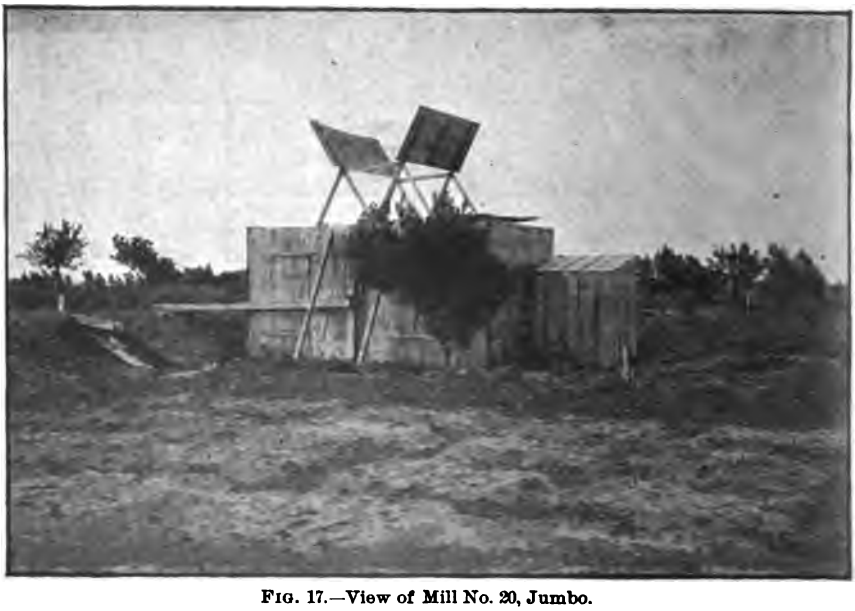
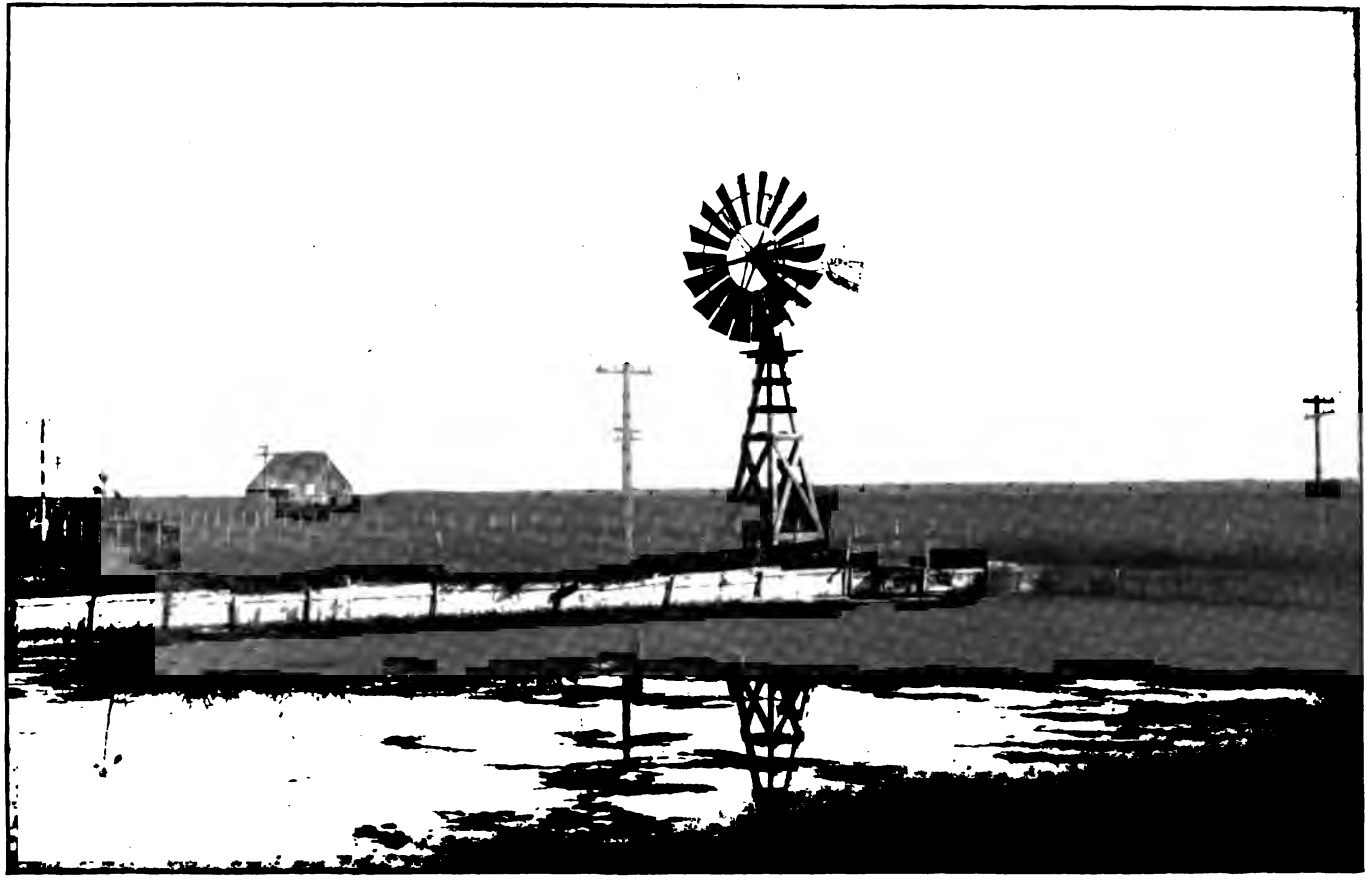


FIG. 17.—View of Mill No. 20, Jumbo.

make, with a discharge pipe 6 inches in diameter; the supply pipe is 4 inches in diameter. There is a 6-inch galvanized iron pipe forming an open well extending 15 feet into the water. The depth to water is 11 feet, the lift is 16 feet, and the discharge per stroke is 3 quarts. The mean barometer pressure was 27.02 inches, and the mean temperature 94° F.

Mill No. 17.—This is a 12-foot improved Gem on a 30-foot steel tower. The wheel has 32 curved fans, each 42 by 11½ by 4¾ inches, set at an angle of 37° with the plane of the wheel. It is back geared 2 to 1. The pump is Gause patent, with an 8-inch discharge pipe, 4-inch supply pipe, 12-inch stroke, and an open well formed of a 12-inch wooden casing. The depth to water is 17¼ feet, the lift 21¾ feet,



VIEW OF MILL NO. 13, AERMOTOR.

and the discharge per stroke 8¾ quarts. The mean barometer pressure was 27.05 inches, and the mean temperature 93° F. This mill, although nearly new, does not work well. It is out of plumb. Only a few measurements of the number of strokes per mile of wind were made.

Mill No. 18.—This is an 8-foot Ideal on a 36-foot wooden tower. The exposure was good, and the parts were in good working order. The wheel is like that of Mill No. 4. The pump is Stone make, with a 6-inch discharge pipe. There is no supply pipe, the cylinder being under water, with 3½ inches opening to it from below. The valves are lift variety for check, and single flap for plunger. The well is open, formed by a 10-inch galvanized pipe in the bottom of a part 4⅓ feet in diameter and 8 feet deep. It is 11 feet to water. The lift is 14¾ feet, and the discharge per stroke 2.92 quarts. The mean barometer pressure was 27.01 inches, and the mean temperature 83° F. The cost of the plant, including pond, was $125.

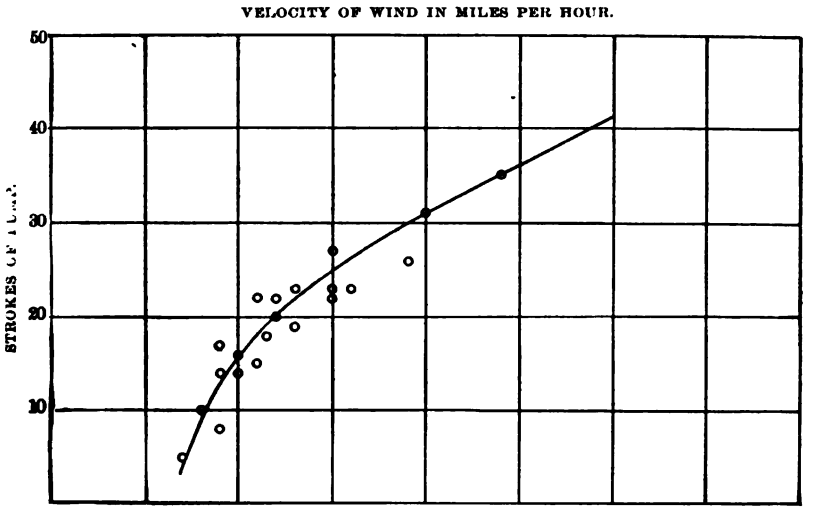


FIG. 18.—Diagram showing results with Mill No. 20.

Mill No. 19.—This is a 12-foot Gem, shown in Pl. VII, on a 30-foot wooden tower. The exposure is good, and the mill is in good working order. The wheel is like that of Mill No. 17. The pump is Stone make, with 10-inch discharge pipe and a 4-inch supply pipe. The length of stroke is 10 inches. The supply pipe is on a 4-inch well point 9 feet long, the end of which is 23 feet below the surface of the ground. The check valve is of the lift type, and the plunger is of the single-flap type. The lift was about 18 feet, and the discharge per stroke 12 quarts. The mean barometer pressure was 27.13 inches, and the mean temperature was 70° F. The water is pumped into a reservoir 120 feet by 60 feet.

The curve, seen in fig. 16, shows that a 9-mile wind is necessary to start this mill, and that the greatest number of strokes per mile of

wind is 45, about 25 per cent less than most 12-foot steel back-geared mills. The piston speed is less than for other 12-foot mills, being at the rate of 6 at 12 miles and at the rate of 16 at 25 miles per hour.

Mill No. 20.—This is a 15½-foot Jumbo, shown in fig. 17. Its axis

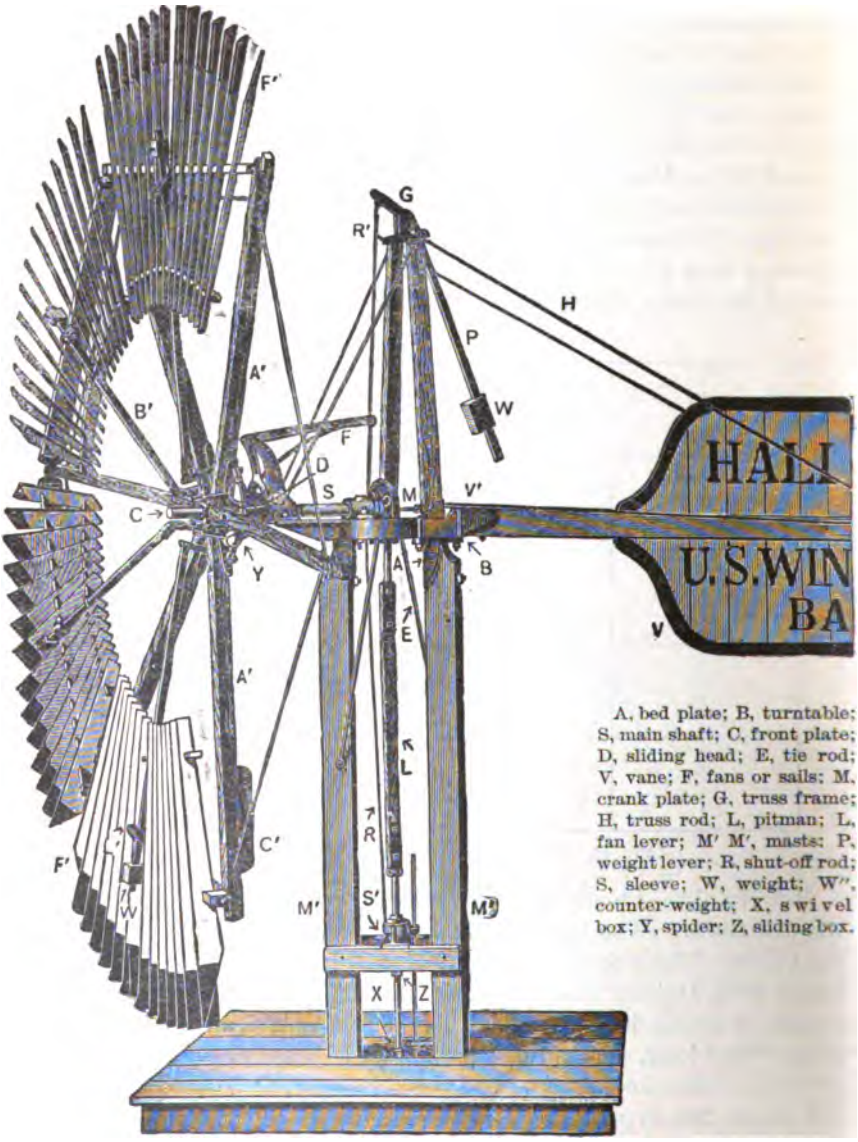


FIG. 19.—Working parts of Halliday mill.

is a steel shaft 8 feet above the ground. It has 6 fans, each 9½ by 3½ feet; the outer radius is 7¾ feet and the inner 4¼ feet. This mill operates two pumps, one at each end of the axis, each having a 6-inch

VIEW OF MILL NO. 19, GEM

cylinder, a 3-inch discharge pipe, and a 3-inch supply pipe on a well point 5 feet long. The discharge of the two pumps was 10 quarts per stroke; the lift was about 14 feet. The mean barometer pressure was 27.09 inches and the mean temperature was 85°. The anemometer was held 14½ feet above the surface of the ground, or at the elevation of the center of a fan when in its highest position. The wheel is set in a large box extending up to a level with the axis of the wheel to prevent the wind from striking the part of the wheel below its axis.

The curve, shown in fig. 18, is seen to be different from the others in that it has no maximum. It starts with a velocity of 13 to 14 miles, and beyond 20 miles it appears to be nearly a straight line.

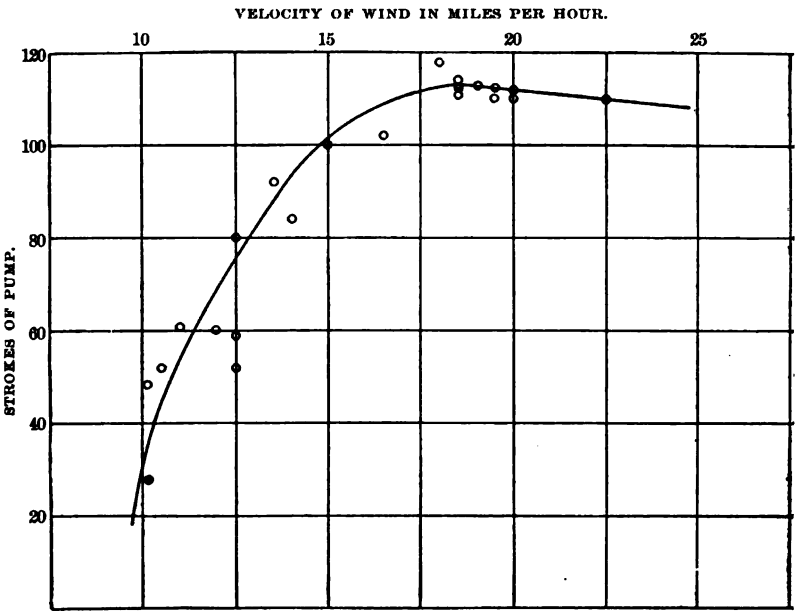


FIG. 20.—Diagram of results with Mill No. 21.

Mill No. 21.—This is a 12-foot Halliday, shown in Pl. VIII, on a 31-foot wooden tower. It was made by the United States Wind Engine and Pump Company, of Batavia, Illinois. The working parts are shown in fig. 19. The wheel has 64 fans, each 42½ by 5 by 2⅜ inches, set at an angle of 35° with the plane of the wheel. It is not back geared, and regulates itself on the centrifugal principle by the fans taking the direction of the wind. The pump is Stone make, with 7½-inch discharge, 4-inch supply pipe, and 7-inch stroke. The check valve is lift form and the plunger double flap. The well is open, formed by a wooden curb 12 inches in diameter sunk in the bottom of a dug well 9 feet deep. The depth to water was 11½ feet and the lift 15 feet. The discharge per stroke was 4½ quarts when pumping quite

rapidly (30 strokes per minute). The valves were not in very good repair, and the pump lost its priming after a time.

This curve, shown in fig. 20, for a lightly loaded (141.5 foot-pounds), direct stroke 12-foot mill, is seen to start with a velocity of 9 to 10 miles, and to reach a maximum at 19 miles, with a piston speed of 112 strokes per mile. At 30 miles the number of strokes is about 98 per mile. The number of strokes per minute varies from 14 at 12 miles to 45 at 25 miles.

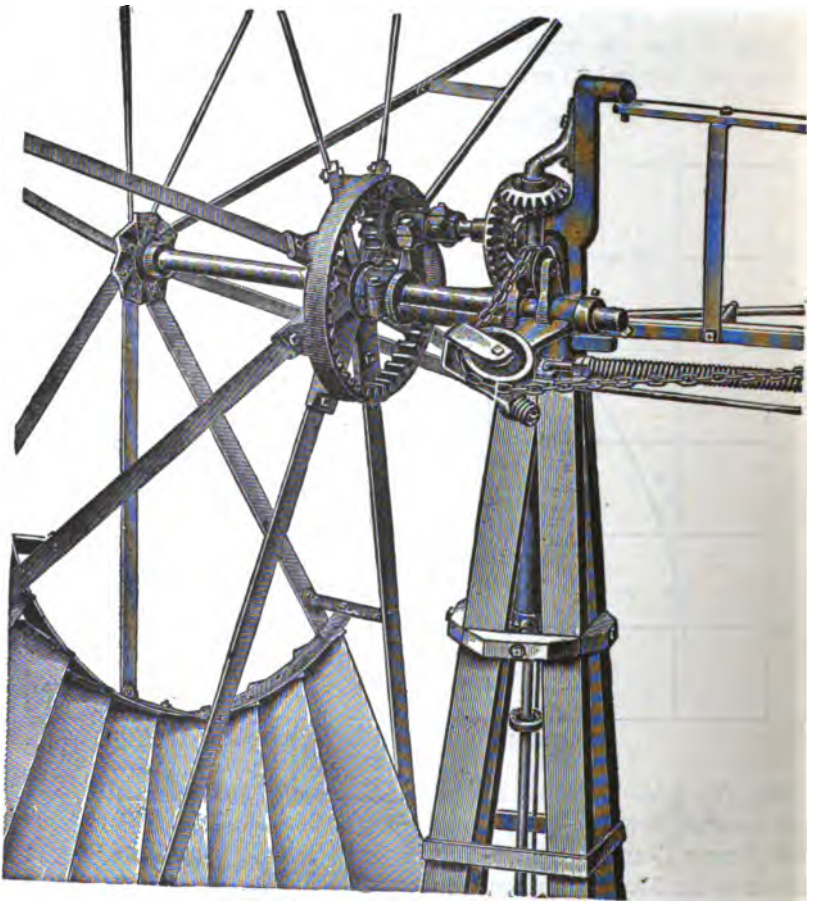


FIG. 21.—Working parts of Power Mill No. 26.

Mills Nos. 22 to 24.—The results obtained from these mills were not sufficiently complete for discussion.

Mill No. 25.—This is an 8-foot steel mill, on a 32-foot steel tower, made by Fairbanks, Morse & Co. The wheel has 18 curved fans, each 29 by 11⅝ by 5¼ inches, set at an angle of 29° with the plane of the wheel. It is back geared 2½ to 1. The pump is of the common hand variety, with 2½-inch cylinder, 1½-inch supply and discharge pipes,

VIEW OF MILL NO. 21, HALLIDAY.

and 4-inch stroke. The well is open 6¼ feet to water. The discharge per stroke was 0.31 quart, and the lift 8½ feet. The water raised is used for watering stock.

Mill No. 26.—This is a 14-foot steel power mill, on a 40-foot steel tower, made by the Perkins Windmill Company, Mishawaka, Indiana.

FIG. 22.—Working parts of Power Mill No. 27.

The working parts are shown in fig. 21. The wheel has 32 curved fans, each 41 by 14¼ by 7¾ inches, set at an angle of 31° with the plane of the wheel. The shaft is geared forward 6 to 1; that is, the shaft makes 6 revolutions to each revolution of the wind wheel. The power was measured by the use of a Prony friction brake. The radius of the brake pulley was 5 inches, and the length of the brake arm 33½

inches. The number of revolutions of the brake pulley per mile of wind was found from a speed counter. This mill was tested twice. Between the dates of testing, some repairs were made to the shafting, causing the cogwheels to bind less tightly. The figures given in Table I for this mill are those obtained from the second test, and are much larger than those from the first test. The load was 6 pounds on the arm 33½ inches long. The mill has been in use about one year.

Mill No. 27.—This is a 12-foot power aermotor on a 30-fo ' steel tower. The wheel is the same as in mill No. 3. The horizontal shaft is geared forward (1. Fig. 22 shows the working parts of the mill and fig. 23 the foot gear. A 9½-inch brake pulley was clamped to the horizontal shaft at *a*, fig. 23. The power was measured by a Prony friction brake on this 9½-inch pulley, the arm of the brake being 35¼ inches in length. The number of revolutions per mile of wind was found from a speed counter. The mean barometer pressure on October 10, 1896, when quite a number of measurements of power were made, was 28.9 inches, and the mean temperature was 46° F. These have been taken as a standard, and measurements made on other days reduced to what they would have been had the pressure been at the standard.

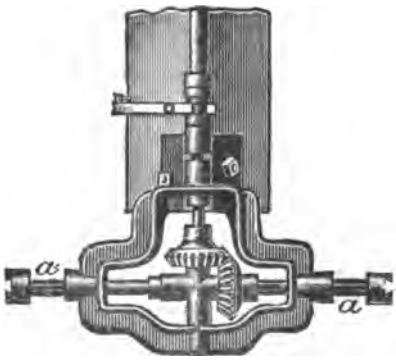


FIG. 23.—Foot gear of power mill No. 27.

DISCUSSION OF THE RESULTS.

The following table gives in condensed form the results obtained from the observations upon the windmills described in the preceding pages. This table shows, first, the arbitrary number given to the mill; next, the name of the mill and that of the owner of the particular one tested. Following this is the diameter of the wind wheel in feet. After this are four general divisions within which the observations have been classified according to the average velocity of the wind in miles per hour, beginning with a wind movement of 8 miles per hour and ending with one of 30 miles per hour. The number of strokes per mile of wind was obtained, as before stated, directly from the record given by the anemometer register. The second set of figures, that giving the number of strokes per minute, is obtained by simple division from the first set, the number of strokes per mile being divided by the number of minutes required for the wind to make a mile. The next set of figures gives the number of gallons per hour that each pump was lifting under the different wind velocities. This is found from the preceding set by multiplying the number of strokes per minute by sixty (number of minutes in an hour), and this by the number of gallons raised at each stroke.

The next set of figures, that giving the useful work in horsepower for the different velocities, is found from the preceding set by multiplying each of these by the factors which convert the number of gallons or the quantity of water raised through the given height into the corresponding horsepower. One horsepower is the rate of work when 33,000 pounds is raised to a height of 1 foot in one minute, or, in other words, is 33,000 foot-pounds. Thus to obtain the useful work in horsepower it is necessary to multiply the number of gallons by the weight in pounds of each gallon and by the height in feet to which this is raised, and to divide this by 33,000. This is expressed mathematically by the simple formula: Horsepower $= \frac{n\,q\,g\,h}{33{,}000}$, where n is the number of strokes per minute, q the number of gallons per stroke, g the weight in pounds per gallon, and h the lift in feet.

FIG. 24.—View of Defender mill and elevator.

The latter part of the table gives, after useful work in horsepower, the foot-pounds of useful work per stroke of the pump, this being obtained in the manner indicated above by multiplying the amount of water in pounds raised each stroke into the height in feet. Next to this is the total vane area of the mill in square feet, this being obtained by a careful measurement of the size of the vanes. Next to this is appended the total lift in feet, obtained as noted under the descriptions of the mills, and also the size of the pump (inside diameter of the cylinder) and the length of stroke, both of these being given in inches.

Results of measurements and computations of pumping mills.

Mill No.	Name.	Owner.	Size.	Number of strokes per mile of wind when velocity per hour in miles is—						Number of strokes per minute when velocity per hour in miles is—					
				8	12	16	20	25	30	8	12	16	20	25	30
			Ft.												
2	Woodmanse	I. L. Diesem	12	.....	26	60	61	56	51	.....	5.2	16.0	20.3	23.3	25.3
3	Aermotor	T. D. Carless	12	40	60	62	60	56	50	5.3	12.0	16.4	19.8	23.1	25.0
4	Ideal	E. S. Austin	8	.....	52	73	76	68	50	.....	10.2	19.3	25.3	28.1	25.0
5	Aermotor	Ella Horner	8	.....	93	94	90	83	77	.....	18.6	25.1	29.8	34.6	38.5
6	Gem	W. J. James	8	.....	62	67	66	61	58	.....	12.4	17.9	22.0	25.4	28.5
7	Aermotor	O. V. Folsom	12	.....	57	59	57	53	47	.....	11.4	15.8	19.0	22.1	23.5
8	Star	J. C. Kitchen	10	210	150	.....	.....	.....	.....	28.0	30.0	.....	.....	.....	.....
9	Aermotor	F. M. Dunn	16	.....	53	53	52	47	42	.....	10.6	14.1	17.2	19.6	21.0
10	Ideal	do	8	106	125	125	.....	.....	.....	14.1	25.0	33.3	.....	.....	.....
11	do	do	12	.....	24	48	57	56	50	.....	4.8	12.7	18.8	23.3	25.0
12	do	D. M. Frost	14	23	55	59	58	52	.....	3.1	10.9	15.7	19.2	21.5	.....
13	Aermotor	Wm. Coulters	12	.....	55	64	63	59	55	.....	11.0	17.1	21.0	24.6	27.5
15	Gem	Jas. Allen	10	.....	39	45	44	35	.....	.....	7.8	11.9	14.7	14.6	.....
16	Halliday	do	10	30	113	127	128	126	.....	4.0	22.6	33.9	42.7	52.5	.....
17	Gem	D. R. Menke	12	.....	39	48	52	.....	.....	.....	6.0	12.8	17.3	.....	.....
18	Ideal	Fred. Pile	8	60	101	a 114 98	102 84	79 66	.....	8.0	20.2	26.1	28.0	27.5	.....
19	Gem	W. E. Trell	12	.....	31	45	44	38	.....	.....	6.2	11.9	14.7	16.0	.....
20	Jumbo	W. T. Cowhick	15½	.....	.....	20	32	42	.....	.....	.....	5.3	10.7	17.5	.....
21	Halliday	J. E. Hunt	12	.....	70	107	112	107	.....	.....	14.0	28.5	37.3	44.6	.....
25	Fairbanks	Wm. Brown	8	92	146	140	114	80	.....	12.3	29.2	37.3	38.0	33.3	.....

Mill No.	Number gallons pumped per hour when wind velocity per hour in miles is—						Useful work in horsepower when wind velocity per hour in miles is—						Foot-pounds useful work per stroke of pump.	Vane area, in square feet.	Lift, feet.	Size of pump. b
	8	12	16	20	25	30	8	12	16	20	25	30				
2	.....	1,131	3,480	4,415	5,069	5,503	.....	.085	.260	.322	.379	.411	536.2	69.4	17.75	9½x12
3	1,153	2,610	3,567	4,306	5,014	5,437	.067	.151	.207	.250	.291	.315	415.3	72.9	13.75	9½x12
4	.....	306	579	759	843	750	.....	.015	.029	.038	.043	.038	50.0	36.1	12.00	5½x8
5	.....	977	1,318	1,564	1,817	2,021	.....	.053	.072	.086	.099	.111	94.9	33.7	13.00	6 x8
6	.....	725	1,047	1,287	1,486	1,667	.....	.029	.042	.051	.059	.065	77.6	36.9	9.60	6½x8
7	.....	2,445	3,387	4,075	4,740	5,041	.....	.160	.221	.266	.309	.329	461.9	72.8	15.50	9½x12
8	101	108	.....	.....	.....	.....	.013	.014	.....	.....	.....	.....	15.0	59.8	30.00	3 x5
9	.....	1,749	2,326	2,838	3,234	3,465	.....	.325	.433	.448	.601	.644	1,013.3	133.6	44.25	8 x16
10	70	125	167	.....	.....	.....	.010	.017	.023	.032	.....	.....	22.8	42.0	33.00	2½x6
11	.....	648	1,714	2,538	3,150	3,375	.....	.123	.325	.481	.600	.639	843.7	75.3	45.00	7½x12
12	535	1,880	2,708	3,312	3,709	.....	.025	.087	.125	.153	.172	.....	263.5	103.6	11.00	9½x12
13	.....	2,376	3,694	4,536	5,314	5,940	.....	.110	.171	.210	.247	.275	330.0	72.8	11.00	10 x12
15	.....	819	1,250	1,543	1,533	.....	.....	.053	.082	.101	.099	.....	219.0	47.3	15.00	8 x8
16	180	1,017	1,526	1,922	2,362	.....	.012	.067	.103	.130	.159	.....	100.0	61.3	16.00	6 x8
17	.....	765	1,632	2,206	.....	.....	.....	.070	c.149	.202	.....	.....	385.0	75.8	21.75	8 x12
18	348	879	1,135	1,218	1,196	.....	.022	.054	(.082) .070	(.062) .076	(.088) .074	.....	89.2	42.0	14.75	5½x8
19	.....	1,116	2,142	2,646	2,880	.....	.....	.085	.162	.201	.219	.....	450.0	77.6	18.00	10 x10
20	.....	.....	795	1,605	2,625	.....	.....	.....	.047	.095	.154	.....	291.2	73.6	14.00	6 x12
21	.....	945	1,924	2,518	3,010	.....	.....	.060	.121	.159	.184	.....	141.5	69.7	15.00	7½x7
25	57	136	173	177	155	.....	.002	.005	.007	.008	.005	.....	5.5	30.2	8.50	2½x4

a Two pumps, each 6 by 12 inches.
b Inside diameter of cylinder by length of stroke.
c Test after increasing the tension of spring which holds wind wheel in the wind.

It is seen that mills of the same size differ very much in the useful work they do, and that some of the large mills are doing very little more work than some of the smaller ones. Nos. 4 and 18 are the same size and make; the wells, however, are very different; the latter is doing two or three times more work than the former. The 12-foot mill, No. 11, is doing nearly as much useful work as the 16-foot mill, No. 9, and three or four times more useful work than the 14-foot mill,

No. 12, while it is doing 300 per cent more work than No. 21. The 15½-foot Jumbo will probably do very little more work during the season than a good 8-foot mill.

RELATION BETWEEN WIND VELOCITY AND STROKES.

The preceding diagrams show graphically the relation between the wind velocity in miles per hour and the strokes of the pump. The curves, as will be noted, differ considerably; but with the exception of No. 23 for Mill No. 20, they agree in that they rise rapidly, reaching the highest point or greatest number of strokes at from 13 to 19 miles of wind velocity. From this point they descend slowly. They differ much in the position of the beginning of the curve, or the velocity required to start the mill. Some will run in an 8-mile wind; others require a 10 or 12 mile wind to start them. Some rise less rapidly than others; a notable case is Mill No. 11. Some descend much more rapidly than others after reaching the highest point. This is especially true of the 8-foot Ideals. Mill No. 12 (Pl. V) required a 14-mile wind to start it, and does not appear to have a maximum.

The shape of the curve, especially the position of its beginning point, is due to the load on the pump, or the number of foot-pounds per stroke. Increasing the load moves the curve to the right and raises it higher. This will be shown more fully in the discussion of power Mill No. 27. The height of the highest point and its position depend on the tension of the spring, or the weight which holds the mill in the wind. The greater the tension, the higher the summit and the farther it is to the right. Mill No. 20 has no method of reducing the wind area, and hence the curve has no summit, as shown in fig. 17. The less the tension in the spring, the steeper the descent from the highest point. The gearing—that is, the mechanism for causing the pump to make a stroke to each revolution of the wheel, or only a stroke every second or third revolution—modifies the curve. If working with a direct stroke, the curve is much higher and is farther to the right than if back geared, as shown by a comparison of mills 3 and 21, shown in figs. 8 and 20.

USEFUL WORK IN HORSEPOWER.

The relation between wind velocity and horsepower is shown graphically for five 12-foot mills on diagram No. 31 and for four 8-foot mills on diagram No. 32. Examining the five curves of fig. 25, we see that No. 11, the one which gives the greatest horsepower, has the heaviest load and requires the greatest wind velocity to start it. No. 2 has about five-eighths the load of No. 11, does less work, and requires about the same wind velocity to start the pump. No. 3 has a lighter load than No. 2 and will start in a wind of about 7 miles per hour. No. 19 has a little heavier load than No. 3 and does much less work

at all velocities. The latter requires a 9 to 10 mile wind to start it, while the former will start in a 7 to 8 mile wind. No. 21 is doing the least work of the five, and requires about an 11-mile wind to start it. It is a wooden mill working direct stroke, while the others are steel mills and back geared. It must be understood in this comparison that no correction or allowance is made for difference in temperature and barometric pressure, nor for the fact that in Nos. 11 and 19 the pumps are in well points, while in the others they are in open wells.

It is seen that in fig. 25 none of these curves reach a maximum

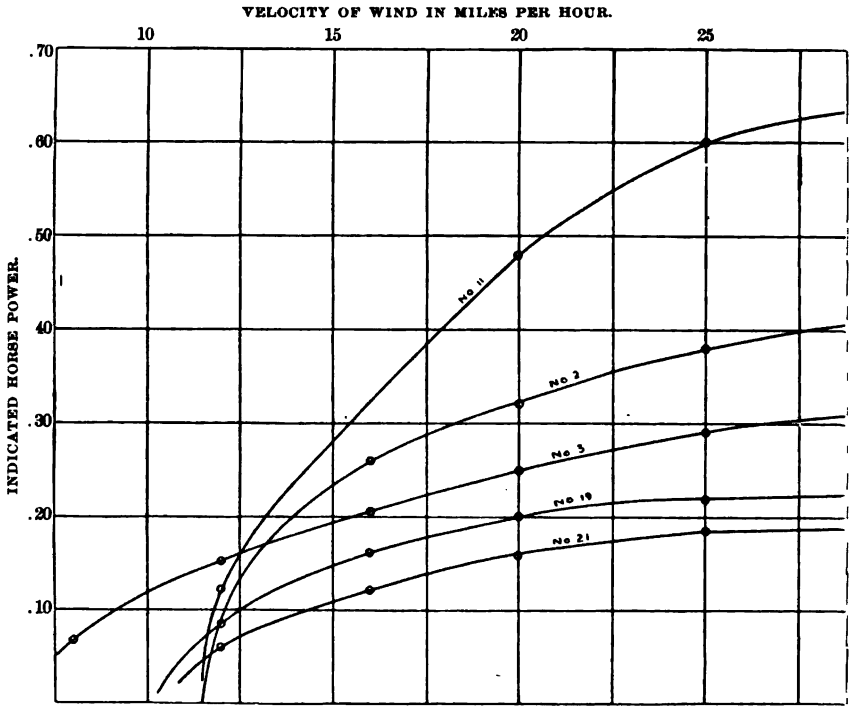


FIG. 25.—Diagram showing relation between horsepower and wind velocity for five 12-foot mills.

point below 30 miles per hour. They do, however, for some higher velocities, since the work per stroke of pump is nearly constant for each pump for all velocities, though not the same for one pump as for another. These curves also give the relation between wind velocity and number of strokes of pump per minute.

In fig. 26 the curve for No. 18 is seen to reach a maximum at 20 miles per hour, and No. 4 reaches a maximum at about 25 miles per hour. The others reach their maximum points for velocities at about 30 miles. These maximum points are points of greatest piston speed, and are produced by a reduction of wind area, the wind wheel turning out of the wind. This make of mill is seen to "govern" or turn out of the wind at a lower velocity than other makes. Comparing the curves on diagram No. 26, we see that the one doing the most work in high velocities is No. 5, the one which is the most heavily loaded. The

principal differences between Nos. 4 and 18—the ones giving the most and the least work for velocities less than 22 miles per hour—are in the load and well. No. 4 has five-ninths of the load of No. 18, and is on a well point. The two doing the least work are on well points.

Mill No. 25 is used to pump water for stock. Comparing it with that of, say, No. 5, we see that its load is about five-ninths, and that it is doing about one-tenth as much work as the latter. It will start with a wind velocity of about 6 miles per hour, while the latter requires a velocity of about 8½ miles.

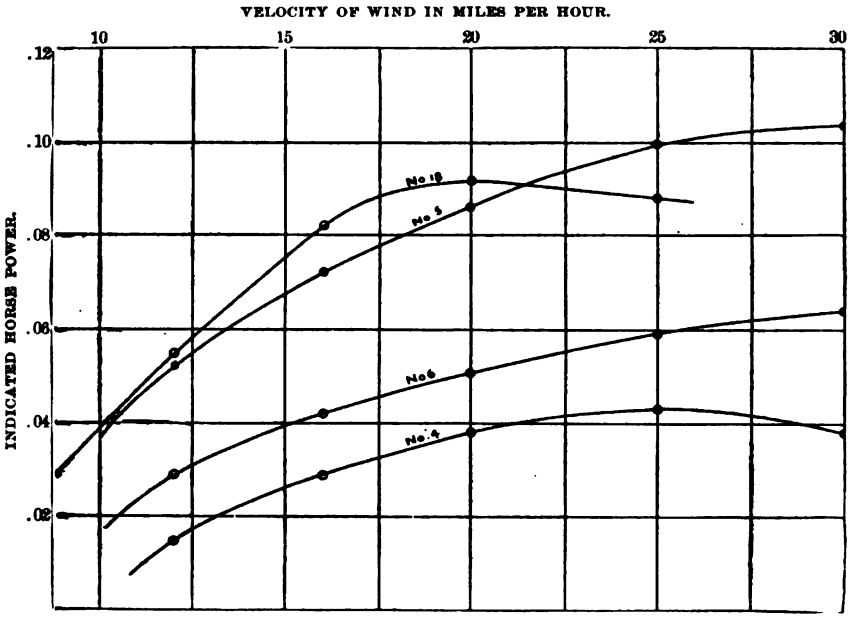


FIG. 26.—Diagram showing relation between horsepower and wind velocity for four 8-foot mills.

COMPARISON OF BACK-GEARED AND DIRECT-STROKE MILLS.

Comparing the curves of fig. 25, which gives the relation between horsepower and wind velocity for five makes of 12-foot mills, we see that the one giving the least power is working direct stroke. It required the greatest velocity to start it, and is doing less work at all velocities than any of the other four. In a 20-mile wind it is making 40 strokes per minute, and in a 25-mile wind 48 strokes per minute. This is too rapid a rate; 30 strokes per minute is as rapid as a pump of this size should work. Hence the horsepower of this mill would be less than shown in the diagram if run at a proper rate. The only way that it can be made to do more work without back gearing it is by increasing the load per stroke, but this will increase the velocity necessary to start it, and cause it to remain idle a greater part of the time. Comparing the working of this mill and, say, No. 3, we see that the work per stroke of No. 3 is 415 foot-pounds and that of No. 21 is 141 foot-pounds, or the former is doing about three times as much

work per stroke as the latter, and the latter is making about 1.8 times as many strokes per minute as the former in a wind velocity of 16 or more miles per hour. The former being back geared 3⅓ to 1, its wheel is revolving about 1.9 times faster than that of the latter. Now, examining the curves of fig. 27, we see that the speed of the wheel has much to do with the useful work done. When the speed is low, as it must be in a mill working direct stroke and not too rapidly for proper action of the valves of the pump, a slight increase in load reduces the speed a good deal. When the speed is nearly doubled, as in the case of Mill No. 3, the load may be increased considerably without reducing the speed much. Hence back gearing not only enables the mill to work with a given load in a much less wind velocity than one working direct stroke with the same load, but it enables the wheel to run at a velocity that gives more power.

PUMP LOAD DUE TO WELL POINT.

On examining well points that have been used for a time, it is seen that many of the little openings through which the water passes into the pump have become filled with fine grains of sand, thus reducing the area through which the water can enter the pump. If this area was of the proper amount when the point was new, it has become too small after having been used for a time, or after standing in the ground for a time without being used. If this area is too small to allow free flow into the pump, an added load is put on the pump.

To measure the mean pull of the pump, an instrument was devised by Mr. R. G. Stone, of Garden, consisting essentially of a spiral spring, whose compression was proportioned to the pull, and a pencil which moved up and down over a smooth surface. The spring was calibrated and the pull in the pump rods of four pumps measured with it. The four pumps selected were operated by the same size and make of mill, and the pumps were the same except as to size of supply pipe, valves, and kind of well. The discharge was practically the same, but the lifts differed slightly. These were Nos. 3, 7, 13, and 22. The following table gives the pull in each case after reducing to a common lift of 17 feet:

Added load due to pump.

No. mill.	Lift.	Kind of well.	Mean pull.
			Pounds.
3	13¾	Open	597
7	17	Open	734
13	12	4-inch well point	944
22	13½	4-inch well point	819

The straining capacity of No. 7 is not as great as that of No. 3, and the resistance of the valves is greater in No. 7 than in No. 3.

USEFUL WORK DONE IN A GIVEN TIME.

The useful work which two mills of the same wind area, exposure, and general character will do depends on the magnitude of the load on the mill and the wind velocity. If the mill is heavily loaded it will do more work in velocities of 12 or more miles per hour, and less in lower velocities than one of a lighter load. The useful work done in a given time is the product of the work done per hour at the mean velocity, and the number of hours during that time. If the mean velocity at a given place is low, the mill load must be less for maximum work than that at a place where the mean velocity is higher. To illustrate this fact we use the results of tests of two 12-foot pumping mills (fig. 25): No. 11, heavily loaded, and giving the greatest horsepower of all the mills tested at high wind velocities; and No. 3, giving the greatest power at low velocities. The useful work per stroke of pump is 844 foot-pounds for No. 11, and 415 foot-pounds for No. 3. The useless work of the former is greater than that of the latter, since the pump is on two well points in the former, while the pump of the latter is in an open well.

The relation between the horsepower and the wind velocity for these mills is shown in the diagram (fig. 25). The curves are seen to cross each other at a wind velocity of 12½ miles per hour. For less velocities than this No. 3 is doing more work per hour than No. 11, and for greater velocities No. 11 is doing more work than No. 3. If the velocity at this place were, say, not more than 13 miles per hour, it is very evident that mill No. 3 would do more work in any time than No. 11.

There is no record of wind movement at Garden, Kansas, for any considerable length of time. There is one, however, for Dodge, 50 miles east of Garden, kept by the United States Weather Bureau, which may be used for this purpose. The following table gives the mean number of hours per month for the six months, April to September, for the seven years 1889 to 1895, that the wind movement was 0–5, 6–10, 11–15, 16–20, 21–25, 26–30, 31 and upward miles per hour.

Mean wind movement at Dodge, Kansas, for the seven years 1889 to 1895.

Months.	0-5	6-10	11-15	16-20	21-25	26-30	31 and upward.
April	116	175	157	113	76	43	40
May	116	195	168	120	74	39	32
June	120	187	139	111	86	49	28
July	144	218	176	117	57	23	9
August	178	230	152	99	62	18	5
September	166	182	152	93	75	34	18
Mean	140	198	157	109	72	34	22

It is seen from this table that the wind velocity is 5 miles or less per hour for 140 hours per month at this place. During this time neither of these mills will do any work, as neither will start in a 5-mile wind. The velocity is from 6 to 10 miles per hour for 198 hours per month. Mill No. 3 will start in about a 7-mile wind, and hence will run about four-fifths of this time, or 158 hours. No. 11 requires 11½ miles of wind to start it, and will do no work during this time. The velocity is 11 to 15 miles per hour for 157 hours during the month. No. 3 will work all of this time, and No. 11 about nine-tenths thereof, or 141 hours. Both mills are running for all higher velocities. Mill No. 3 will run (if in the wind) about 75 per cent of the time at this place, and No. 11 about 51 per cent of the time.

Comparative performance of two mills.

Velocities.	Mill No. 3.			Mill No. 11.		
	Hours.	Power.	Product.	Hours.	Power.	Product.
6–10	158	0.067	10.6	0	0.0	0.0
11–15	157	.168	26.4	141	.19	26.8
16–20	109	.230	25.1	109	.40	43.6
21–25	72	.277	19.9	72	.56	40.3
26–30	34	.308	10.5	34	.63	21.4
31 and upward	22	.320	7.0	22	.64	14.1
Sum			99.5			146.2

Columns 2 and 5 of the above table give the number of hours during the mean month that each mill was running with a wind velocity of from 6 to 10, etc., miles per hour. Columns 3 and 6 give the horsepower for the mean velocity; for example, 0.168 is the horsepower for No. 3 at 13 miles per hour, and 0.19 is the horsepower for No. 11 for the same velocity. Columns 4 and 7 give the product of the number of hours and horsepower that each mill is yielding during the month. It is seen that No. 11 is doing 31 per cent more useful work than No. 3. If this comparison is made for the month of August, it will be found that No. 11 will do 26 per cent more useful work during this month than No. 3.

POWER MILLS.

The working parts of Power Mill No. 27 are shown in fig. 22. Instead of the reciprocating motion of the pumping mill, there is here a central shaft which is caused to rotate by beveled cog wheels. The sizes of the cog wheels are so taken that this central shaft makes six revolutions to one of the wind wheel. The pumping mill being back geared 3⅓ to 1, and the power mill being geared forward 6 to 1, the vertical shaft makes twenty revolutions to one stroke of a pump

worked by a pumping mill whose wind wheel is running at the same rate as that of a power mill. At the lower end of this shaft is a foot gear, shown in fig. 23, on which is placed the pulley which runs the grinder or other machine.

The power that a windmill is capable of developing can be determined better from a power than from a pumping mill, because the efficiency of the pump, which may be anything from 20 per cent to 85 per cent, is eliminated, and because the load on the mill can be varied at will, and thus the effect of load on the power can be determined for different wind velocities. To measure the power of this mill a pulley 9½ inches in diameter was fitted to the shaft at A, fig. 23, and a Prony friction brake, having an arm about 3 feet long, made to fit the pulley. A spring balance reading to quarters of a pound was made fast at one end, the other end being fastened to the arm of the brake. The speed of the shaft was found to be too great to be taken by a recorder, so a speed counter was used. By turning the nuts on the under side of the brake the spring balance could be made to read any desired number of pounds, and thus the load on the mill could be regulated. By holding the speed counter on the end of the shaft, throwing it in gear at the beginning of a mile of wind and throwing it out of gear at the end of the mile, the number of revolutions of pulley was found. The time of making the mile was also noted, from which wind velocity was found. If u equal the number of revolutions of pulley per mile of wind, L the load as shown by spring balance plus load of arm, and R the length of brake arm, we have the number of foot-pounds per mile of wind: Foot-pounds$=L\,u\,2\,\pi\,R$.

In fig. 27 are given four curves showing the relation between the number of foot-pounds per mile of wind and the wind velocity for four loads, namely, 6 pounds, 4 pounds, 2 pounds, and 0 pounds. These curves are constructed in the same way as those of figs. 4, 8, 9, 11, 13, 15, 16, 18, and 20, by drawing a smooth curve among a series of points whose ordinates are found from the above equation and whose abscissas are the observed velocity of wind, so as to have about as many points on one side as on the other. The left, or steep part, of each curve is the most difficult to determine, and has a less degree of accuracy than the rest of the curve; owing to the velocity being low, several minutes are necessary to make a mile, and the wind may vary considerably during this time. It may be nearly an average all the time and the mill scarcely move, or it may be twice as rapid the latter half of the time as the first half, and the number of revolutions for the same mean velocity will be quite different in the two cases.

Another reason why the steep part is less accurate is that a very little movement to the right or left of this portion will change the number of foot-pounds much more than in any other part of the curve. The curve A B is for no brake load. The brake was off the pulley; no useful work was being done, but the resistance of the moving parts

of the mill was being overcome. The pull necessary to overcome this resistance was found by standing on the platform of the mill and pulling the wind wheel around at uniform low speed with a spring balance. This was checked by winding a cord round the circumference of the wind wheel, and, standing on the ground, moving the mill when there

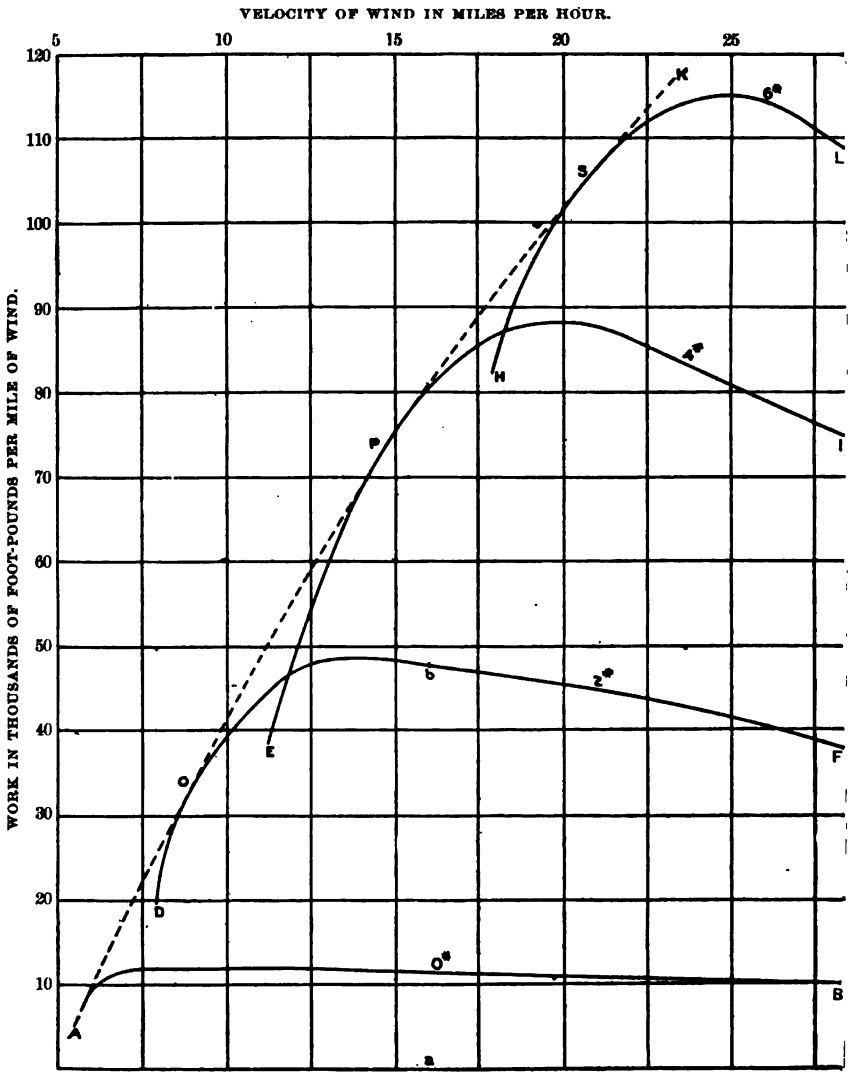


FIG. 27.—Diagram showing useful work for different loads of Mill No. 27.

was no wind by pulling on the spring balance attached to this cord. A pull of 1¼ pounds applied at the circumference (6 feet from center of wind wheel) was sufficient to overcome this resistance at a low velocity. Since the brake pulley is geared forward 6 to 1, the number of foot-pounds per revolution of brake pulley necessary to overcome this

resistance is 7.9. The number of foot-pounds per mile of wind for other velocities is then easily found from speed of brake pulley.

The greater part of this curve, A B, fig. 27, is seen to be a nearly horizontal straight line, the number of foot-pounds per mile of wind required to run the machinery being nearly constant. The other three curves of this plate are for useful work only; the useless work is not included in them. The highest point of these curves is seen to rise and move to the right as the load increases, and the part to the right of the highest point is seen to become more and more steep as the load increases. A broken line, A K, has been sketched tangent

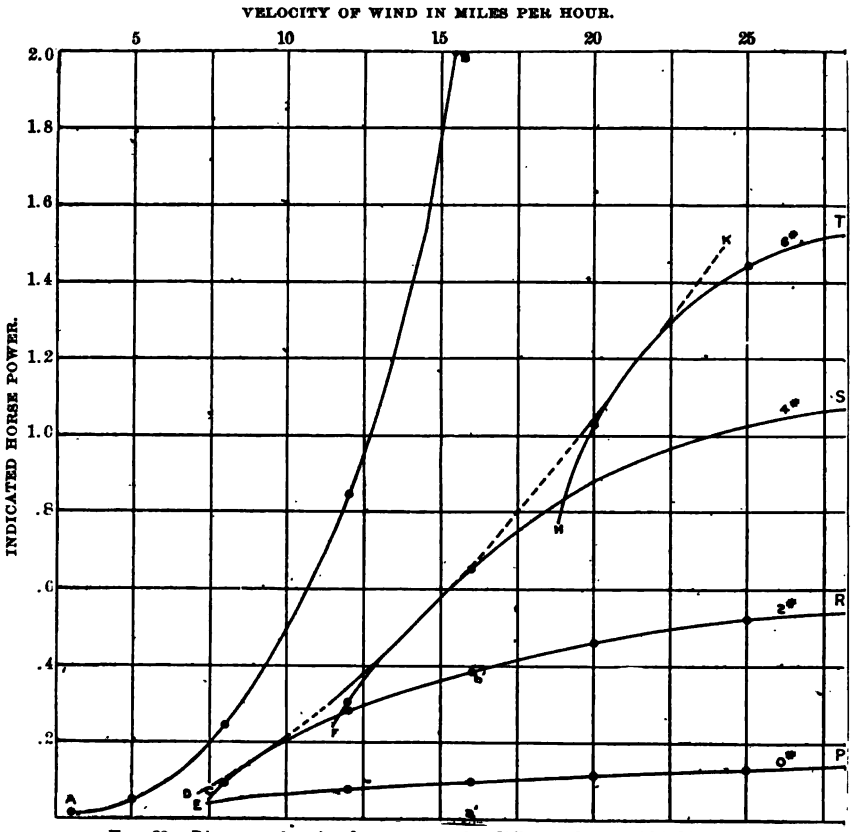


FIG. 28.—Diagram showing horsepower for different loads of Mill No. 27.

to these curves. It is the envelope of them and is concave to the horizontal coordinate axis. It would give the relation between foot-pounds per mile of wind and wind velocity if the load could be increased as the velocity increases.

Fig. 28 shows the relation between the horsepower and the wind velocity for the four loads—6 pounds, 4 pounds, 2 pounds, and 0 pounds. They are obtained from the curves of fig. 27 by reducing foot-pounds per mile of wind to horsepower; that is, for any velocity of, say, 16 miles per hour and load of, say, 2 pounds, divide

the ordinate a b, fig. 27, by $\frac{60}{16}$ (the number of minutes required to make the mile), and by 33,000, and we have the corresponding ordinate a′ b′ of fig. 28.

It is seen from these curves that for any brake load the power of the mill increases rapidly as the wind velocity increases, and reaches a maximum for some velocity greater than 30 miles per hour. As the load increases, the velocity required to start the mill increases rapidly and the curve becomes more steep. For a given wind velocity the power increases rapidly as the load increases. For a velocity of 30 miles the power is nearly proportional to the load for loads less than 6 pounds. It is seen that when the velocity is less than 12 miles a 4-pound load is too great, and when the velocity is less than 19 miles a 6-pound load is too great. The dotted curve D K, which is the envelope of these curves, gives the relation between power and wind velocity for a constantly increasing load. It is seen that there would be a great saving of power by the use of a device which would automatically increase the load as the velocity increases. The horsepower would then be given by the curve D K, instead of by one of the other curves.

Results of computations of power mills.

Mill No.	Name.	Owner.	Size.	Brake load.	Foot-pounds per mile of wind when hourly velocity in miles is—					
					8	12	16	20	25	30
			Ft.	*Lbs.*						
26	Perkins	Geo. Gilbert	14	6	.....	.....	.....	.....	.....	.....
27	Aermotor	E. C. Murphy	12	6	.....	.....	.....	101,500	115,000	104,200
27	do	do	12	4	.....	50,000	80,800	88,400	80,800	71,700
27	do	do	12	2	22,000	47,000	47,800	45,400	41,400	35,600
27	do	do	12	0	12,000	12,000	11,400	11,000	10,200	9,700

Mill No.	Brake load.	Foot-pounds per minute when hourly wind velocity in miles is—						Useful work in horse power when hourly wind velocity in miles is—						Vane area in square feet.
		8	12	16	20	25	30	8	12	16	20	25	30	
	Lbs.													
26	6	.....	.....	.....	.....	.....	.....	.....	.....	.313	.609	.937	.....	100.2
27	6	.....	.....	.....	33,833	47,917	52,100	.....	.....	.....	1.028	1.451	1.576	72.9
27	4	.....	10,000	21,530	29,367	33,667	35,850	.....	.303	.653	.890	1.020	1.086	72.9
27	2	2,933	9,400	12,747	15,133	17,250	17,800	.089	.285	.386	.458	.523	.540	72.9
27	0	1,600	2,400	3,040	3,667	4,250	4,850	.050	.073	.087	.111	.128	.151	72.9

TOTAL ENERGY OF THE WIND.

The curve A B shows the relation between wind velocity and the total horsepower possessed by the wind at the temperature of 46° F. and the barometric pressure of 28.9 inches. It is found from the relation Horsepower$=\frac{w}{2g}$ A $\frac{V^3}{550}$ where w is the weight per cubic foot of air at this temperature and pressure, A the vane area equals 72.9

square feet, V the velocity of wind in feet per second, and g the acceleration of gravity. w was found from the formula $w = \frac{T_0}{p_0} w_0 \frac{p}{T}$,[1] in which $T_0 = 273°$ C., $w_0 = .0807$ pounds per cubic foot, $p_0 = 14.7$ pounds per square inch, $T = 281°$ C., $p = 28.9$ inches, and C = the temperature expressed in centigrade degrees. Substituting these values, Horsepower = $.00021\ V^3$.

EFFICIENCY OF MILL.

By dividing any ordinate of a load curve by the corresponding ordinate of this curve A B, we have the efficiency of the mill for this load and velocity of wind. It is easily seen that the efficiency increases as the velocity decreases and as the load increases. The maximum efficiency is given by the ratio of the ordinate of the dotted curve to the corresponding ordinate of curve A B. This efficiency for a load of 2 pounds and a velocity of 9 miles per hour is 40 per cent, using as wind area the sum of the areas of the fans. At 14 miles with a load of 4 pounds it is 36 per cent. If the load at this velocity be reduced to 2 pounds the efficiency is reduced to 24 per cent.

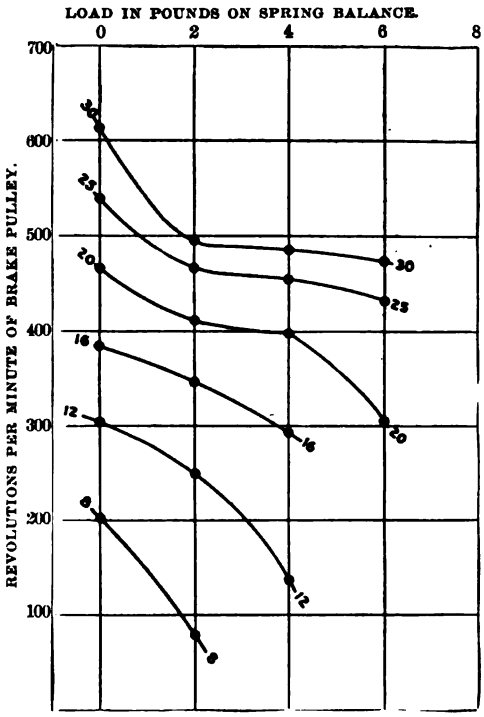


FIG. 29.—Diagram showing relation between number of revolutions of brake pulley per minute and load for different wind velocities for Mill No. 27.

Fig. 29 shows the relation between load and number of revolutions of the brake pulley for velocities of 8, 12, 16, 20, 25, and 30 miles per hour. It shows how much the speed is reduced by a given change of load. It is seen that for a velocity of 8 miles per hour changing the load from 0 to 2 pounds reduces the speed 60 per cent. When the velocity is 12 miles, changing the load from 0 to 2 pounds reduces the speed about 17 per cent, and changing from 2 to 4 pounds reduces it nearly 50 per cent. When the velocity is 16 miles, changing the load from 0 to 2 pounds changes the speed very little. When the velocity is 20 miles, the speed remains about constant for 2 and 4

[1] I. P. Churche's Mechanics of Engineering, p. 611, John Wiley & Sons, New York. Table giving results of computations of power mills.

pounds; at 25 and 30 miles the speed remains nearly constant for loads from 2 to 6 pounds.

MATHEMATICAL RELATION BETWEEN WIND VELOCITY AND POWER.

The relation between wind velocity and power of windmill is expressed graphically by the curves of fig. 28. The mathematical expression of this relation is given by Mr. A. R. Wolff on page 30 of his book, The Windmill as a Prime Motor, as Lv (or foot-pounds per second) $= \frac{s\,k\,c^2\,d}{g}\,v\left(\sin\alpha - \frac{v}{c}\cos\alpha\right)\cos\alpha$, where v=velocity of fan, s=surface of fan in feet, c=velocity of wind in feet per second, L=useful wind pressure on fan, d=density of wind, g=acceleration due to gravity, k is a coefficient, and α=the angle that the wind makes with surface of fan. It is seen that for a given wind velocity, density of air, and wind area, this expression for useful work is a function only of the velocity of the moving fan; it is not a function of the load on the mill. Fig. 29 shows that for a wind velocity of 30 miles per hour, and with a nearly constant velocity of wind area (v in the above formula), the load can be more than double, and thus the power more than doubled. It is evident, then, that however well this formula may give the power of the old Dutch mill or other modern mills not back geared, it gives results very much in error for a steel back-geared mill. Judging from the results of these tests, a formula giving the power of a steel back-geared mill should contain a factor which varies as the load on the mill varies.

GENERAL CONCLUSIONS.

1. The pumping power of windmills, or the useful work they do when raising water with reciprocating pumps of sizes from 4 to 10 inches diameter, is small—not greater that 0.65 of 1 horsepower for 12-foot mills, and much less than that claimed for them by some windmill makers.

2. The pumping power of windmills made for irrigating purposes is much greater than that of those which have been used for raising water for stock purposes.

3. The pumping power of the steel back-geared mills is greater than that of the wooden mills working with direct stroke.

4. The power of the Jumbo mill is much less—except for very high wind velocities—than that of the steel back-geared mills.

5. Well points produce a greater load on a windmill for a given lift and quantity of water than open wells.

6. Perhaps the most important result shown by these tests, and one that has not been clearly shown before, as far as the writer has seen,[1]

[1] Abstract of paper on "Windmills for raising water," by J. A. Griffiths: Proc. Inst. Civil Eng., Vol. 119, 1895, p. 15.

matically increasing the load as the wind velocity increases, the power may be much increased at high velocities, and will then vary as the second power of the velocity. Even with this device for increasing power there is still a great difference between the power possessed by the wind and the power developed by the mill, and this difference increases as the velocity increases.

The reason why the windmill utilizes so small an amount of the energy of the wind may be seen from the following: Let A B, fig. 30, be a strip taken from the outer end of one fan of a windmill. It is curved, but for this purpose it may be considered a plane. This strip makes an angle α with the absolute direction of the wind. C represents the amount and direction of the wind; V represents the amount and direction of the velocity of the surface A B. Then the relative velocity of the wind—that is, its velocity with respect to the moving surface A B—is V′, the diagonal of the parallelogram constructed on V and C as sides, V′ makes an angle β with the sloping surface A B. If V=0—that is, if the wheel is held so that it can not revolve—the angle $\beta=\alpha$. As V increases β grows less and less, and finally becomes zero, in which case V′ is parallel to surface A B. In this case the surface receives no pressure from the wind—this portion of the fan is not utilizing any of the energy of the wind. If V be still further increased, β becomes negative, and the wind pressure is on the opposite side of A B. This portion of the fan is then doing work on the wind instead of the wind doing work on the fan. The effective wind area of a fan being the projection of the fan on a plane at right angles to the relative velocity of wind over it—that is, to V′—it is seen that as V increases the effective wind area decreases. The energy which the fan takes from the wind is proportional to the effective wind area. It is seen, then, that this reduction of effective wind area is the reason why the efficiency is low at high velocities. If this effective wind area could be kept constant by some device for changing the angle of the fans, the relation between wind velocity and horsepower might vary nearly as the third power of the wind velocity.

In this discussion we have not taken into account the reduction of wind area due to the wind wheel swinging out of the wind, or "regulating." The mill can be built strong enough so that it will not need to regulate for velocities less than 30 miles an hour.

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1895.

Sixteenth Annual Report of the United States Geological Survey, 1894–95, Part II, Papers of an economic character, 1895, octavo, 598 pp.

Contains a paper on the public lands and their water supply, by F. H. Newell, illustrated by a large map showing the relative extent and location of the vacant public lands; also a report on the water resources of a portion of the Great Plains, by Robert Hay.

A geological reconnoissance of northwestern Wyoming, by George H. Eldridge, 1894, octavo, 72 pp. Bulletin No. 119 of the United States Geological Survey; price, 10 cents.

Contains a description of the geologic structure of portions of the Big Horn Range and Big Horn Basin, especially with reference to the coal fields, and remarks upon the water supply and agricultural possibilities.

Report of progress of the division of hydrography for the calendar year 1893–94, by F. H. Newell, 1895, octavo, 176 pp. Bulletin No. 131 of the United States Geological Survey; price, 15 cents.

Contains results of stream measurements at various points, mainly within the arid region, and records of wells in a number of counties in western Nebraska, western Kansas, and eastern Colorado.

1896.

Seventeenth Annual Report of the United States Geological Survey, 1895–96, Part II, Economic geology and hydrography, 1896, octavo, 864 pp.

Contains papers by G. K. Gilbert on the underground water of the Arkansas Valley in eastern Colorado; by Frank Leverett on the water resources of Illinois; and by N. H. Darton on a reconnoissance of the artesian areas of a portion of the Dakotas.

Artesian-well prospects in the Atlantic Coastal Plain region, by N. H. Darton, 1896, octavo, 230 pp., 19 plates. Bulletin No. 138 of the United States Geological Survey; price, 20 cents.

Gives a description of the geologic conditions of the coastal region from Long Island, N. Y., to Georgia, and contains data relating to many of the deep wells.

Report of progress of the division of hydrography for the calendar year 1895, by F. H. Newell, hydrographer in charge, 1896, octavo, 356 pp. Bulletin No. 140 of the United States Geological Survey; price, 25 cents.

Contains a description of the instruments and methods employed in measuring streams and the results of hydrographic investigations in various parts of the United States.

1897.

Eighteenth Annual Report of the United States Geological Survey, 1896–97, Part IV, Hydrography, 1897, octavo, — pp. (In preparation.)

Contains a progress report of stream measurements for the year 1896, by Arthur P. Davis, and four other papers relating to hydrography. The first of these is by Frank Leverett, and relates to the water resources of Ohio and Indiana, especially as obtained by wells; the next is by N. H. Darton, on the artesian waters of South Dakota, being supplementary to his paper in the Seventeenth Annual; following this is a fully illustrated paper, by James D. Schuyler, on water storage, mainly for irrigation and the construction of dams; the last paper, by Robert T. Hill, describes the artesian conditions of a portion of Texas in the vicinity of San Antonio.

Water Supply and Irrigation Papers.

This series of papers is designed to present in pamphlet form the results of stream measurements and of special investigations. A list of these, with other information, is given on the outside (or fourth) page of this cover.

Survey bulletins can be obtained only by prepayment of cost as noted above. Postage stamps, checks, and drafts can not be accepted. Money should be transmitted by postal money order or express order, made payable to the Director of the United States Geological Survey. Correspondence relating to the publications of the Survey should be addressed to **The Director, United States Geological Survey, Washington, D. C.**

WATER-SUPPLY AND IRRIGATION PAPERS.

1. Pumping water for irrigation, by Herbert M. Wilson, 1896.
2. Irrigation near Phœnix, Arizona, by Arthur P. Davis, 1897.
3. Sewage irrigation, by George W. Rafter, 1897.
4. A reconnoissance in southeastern Washington, by Israel C. Russell, 1897.
5. Irrigation practice on the Great Plains, by E. B. Cowgill, 1897.
6. Underground waters of southwestern Kansas, by Erasmus Haworth, 1897.
7. Seepage waters of northern Utah, by Samuel Fortier.
8. Windmills for irrigation, by E. C. Murphy.

In preparation:

9. Irrigation near Greeley, Colorado, by David Boyd.
10. Irrigation in Mesilla Valley, New Mexico, by F. C. Barker.
11. River heights for 1896, by Arthur P. Davis.
12. Water resources of southeastern Nebraska, by Nelson Horatio Darton.

In addition to the above, there are in various stages of preparation other papers relating to the measurement of streams, the storage of water, the amount available from underground sources, the efficiency of windmills, the cost of pumping, and other details relating to the methods of utilizing the water resources of the country. Provision has been made for printing these by the following clause in the sundry civil act making appropriations for the year 1896–97:

Provided, That hereafter the reports of the Geological Survey in relation to the gauging of streams and to the methods of utilizing the water resources may be printed in octavo form, not to exceed 100 pages in length and 5,000 copies in number; 1,000 copies of which shall be for the official use of the Geological Survey, 1,500 copies shall be delivered to the Senate, and 2,500 copies shall be delivered to the House of Representatives, for distribution. (Approved, June 11, 1896; Stat. L., vol. 29, p. 453.)

The maximum number of copies available for the use of the Geological Survey is 1,000. This quantity falls far short of the demand, so that it is impossible to supply all requests. Attempts are made to send these pamphlets to persons who have rendered assistance in their preparation through replies to schedules or donation of data. Requests specifying a certain paper and stating a reason for asking for it are attended to whenever practicable, but it is impossible to comply with general demands, such as to have all of the series sent indiscriminately.

Application for these papers should be made either to Members of Congress or to

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